ENGINEERING EVALUATION OF THE RED BLUFF RESEARCH PUMPING PLANT ON THE SACRAMENTO RIVER IN NORTHERN CALIFORNIA: 1995-1998

A Summary Report
Red Bluff Research Pumping Plant
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Prepared By:

K. W. Frizell
Bureau of Reclamation
Water Resources Research Laboratory
P.O. Box 25007
Denver, CO 80225-0007

S. P. Atkinson
Bureau of Reclamation
Flaming Gorge Field Division
P.O. Box 278
Dutch John, UT 84023-0278

Prepared For:

Bureau of Reclamation
Red Bluff Fish Passage Program
P.O. Box 159
Red Bluff, CA 96080

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Summary Report

K.W. Frizell and S.P. Atkinson[1]

Bureau of Reclamation
Water Resources Research Laboratory
Denver Technical Services Center
P.O. Box 25007
Denver, CO 80225-0007

Abstract. The Red Bluff Research Pumping Plant was constructed to allow evaluation of up to four different types of pumps for their ability to provide pumped irrigation and/or bypass flows without adversely impacting Sacramento River fish populations. Archimedes pumps and a centrifugal pump with a helical screw-shaped impeller are currently being evaluated. Major plant construction was completed in 1995. Subsequent to that date, engineering and biological evaluations have been ongoing. Over the course of the study, the general goals of the engineering evaluation have remained constant; however, specific objectives have changed and evolved due to the dynamic nature of operating the pumping plant.

This report summarizes engineering activities from 1995-1998 related to Red Bluff Research Pumping Plant operations and performance. Included are not only the pump specific studies but evaluation of many of the appurtenant structures which interface the pumping plant with the river. The pumps have operated rather sporadically during the evaluation period for a variety of reasons. Problems have been identified and corrected. Some of the initial perceived problems have not materialized and some of the site-specific evaluations concerning construction of a much larger pumping facility have taken on less importance. Unlike the typical research report format, this summary report will report on background, past studies, and present studies in several key areas which have been identified for evaluations.

[1]Present address is Bureau of Reclamation, Flaming Gorge Field Division - FG-200, PO Box 278, Dutch John UT 84023-0278

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Introduction

In 1995, construction was completed on a demonstration pump project located just downstream from the Red Bluff Diversion Dam (RBDD) on the Sacramento River in northern California. The Red Bluff Research Pumping Plant (RBRPP) was constructed to allow the evaluation of up to four different types of pumps for their ability to provide water deliveries to the Tehama-Colusa Canal System [Liston and Johnson 1992a]. To be a viable alternative to the present diversion dam and gravity diversion, water deliveries must not adversely impact the fisheries resources in the Sacramento River. The Sacramento River at this location has been regulated by Shasta Dam since December 1943. In 1964, the Red Bluff Diversion Dam was completed and water deliveries by gravity diversion to the Tehama-Colusa Canal System began in 1966. The Red Bluff Diversion Dam is used to control the water surface in Lake Red Bluff during the irrigation season. This control is accomplished using eleven 60- by 18-ft regulating gates. The gate on the far right side of the dam is used as a sluice gate. This gate has automatic controls to aid in maintaining a constant water surface elevation in Lake Red Bluff and to sluice sediment from in front of the canal headworks.

Operations of the RBDD have adversely affected the fisheries resources in the river, in particular the populations of anadromous salmon and steelhead. Delayed passage through right and left abutment fish ladders of up-migrating adults, and induced mortalities of down-migrating juveniles have been major problems resulting from RBDD gate operations. In efforts to improve the fisheries resources, federal and state agencies agreed to raise the gates at RBDD in order to return the Sacramento River at Red Bluff to pre-diversion dam conditions. During 1986 to 1993, the gates at RBDD were raised on various schedules during winter and spring. In 1993, the National Marine Fisheries Service [1993a, 1993b] formally directed Reclamation to raise the gates on the RBDD beginning on September 15 and extending through May 15 of the following calendar year (8 months). This operation allows for water deliveries from Lake Red Bluff during the high irrigation demands in summer, allows for high rates of free passage of three of the four chinook salmon runs and the steelhead run to upstream spawning grounds, and provides for high rates of unimpeded out migration of all juveniles.

This period of gates-up operation impacts the irrigation season for the Tehama-Colusa canal water users. Temporary pumps have been installed near the right abutment fish ladder to supplement water to the canal once the gates are raised and gravity diversion is no longer possible. Operation of the RBRPP also allows for supplemental flows to the canal during these periods. Evaluations of the pumps can take place any time of the year, as long as the Sacramento River at the plant location is below elevation 245 ft. The summer months are the most desired engineering evaluation period, due to low river levels and complete freedom to operate the pumps without impacting the canal system. However, biological evaluations are better done in the spring and fall.

The Evaluation Plan and Study Areas

The goals of the engineering studies were first detailed in Liston and Johnson [1992b]. These original goals as stated were:

- Establish the performance characteristics of the pumps including optimum pump speed and corresponding discharge (will incorporate biological data and develop data on maintenance requirements, capital and operating costs.
- Develop pump accessory design features that will minimize maintenance requirements and maximize pump performance (Archimedes pump seal, lower bearings, intake bell, etc.)
- Refine trashrack structure to maintain strong sweeping flows past pumps and thus minimize debris and sediment accumulation while guiding fish away from the pumps.
- Quantify debris and sediment loads at the site.
- Use the RBRPP to develop optimum design features for a potential larger pumping facility.

These basic goals have remained intact during the course of the evaluations with completion of many varied tasks associated with accomplishing these goals. As with any long-term project, the execution of particular tasks may change due to a variety of reasons. Recently the goals and objectives were reevaluated and defined as follows:

> **GOAL:** *To provide engineering assessments and modifications as needed to assure trouble free long-term operations and appropriate hydraulic conditions at fish screens and bypasses, and to supply critical hydraulic information for interpreting fisheries data.*

To accomplish this goal, several objectives or tasks were identified:

- Establish the performance characteristics of the pumps, including optimum pump speed for given river conditions.
- Develop accessory features that will minimize maintenance requirements and maximize pump performance.
- Refine trashrack structure to maintain strong sweeping flows past pumps and thus minimize debris and sediment accumulation and fish entrainment.
- Assess effects of debris fouling and sedimentation on fish screen and fish evaluation facilities.
- Modify fish screen structures to insure proper velocity magnitudes and distributions to meet State and Federal standards.
- Incorporate monitoring devices on plant features to assist in operations and maintenance activities.
- Incorporate changes to the bypass and fish holding facilities to minimize harmful hydraulic conditions.
- Develop general design features for a potential larger pumping facility at Red Bluff.

A further discussion of the means to achieve these goals and objectives can be found in Frizell and Atkinson [1996]. To aid in the engineering evaluation, the site was divided into several study areas. This division follows a logical separation of the major components of the pumping plant and surrounding areas, figure 1. The major divisions are: the Sacramento River, the inlet structure, the pumps, the pump discharge channels and fish screen structure, the fish evaluation and bypass facilities, and the canal discharge. This report will discuss each area, giving background information, results of previous studies, and methods and results of specific current investigations associated with a particular study area. A general discussion will follow.

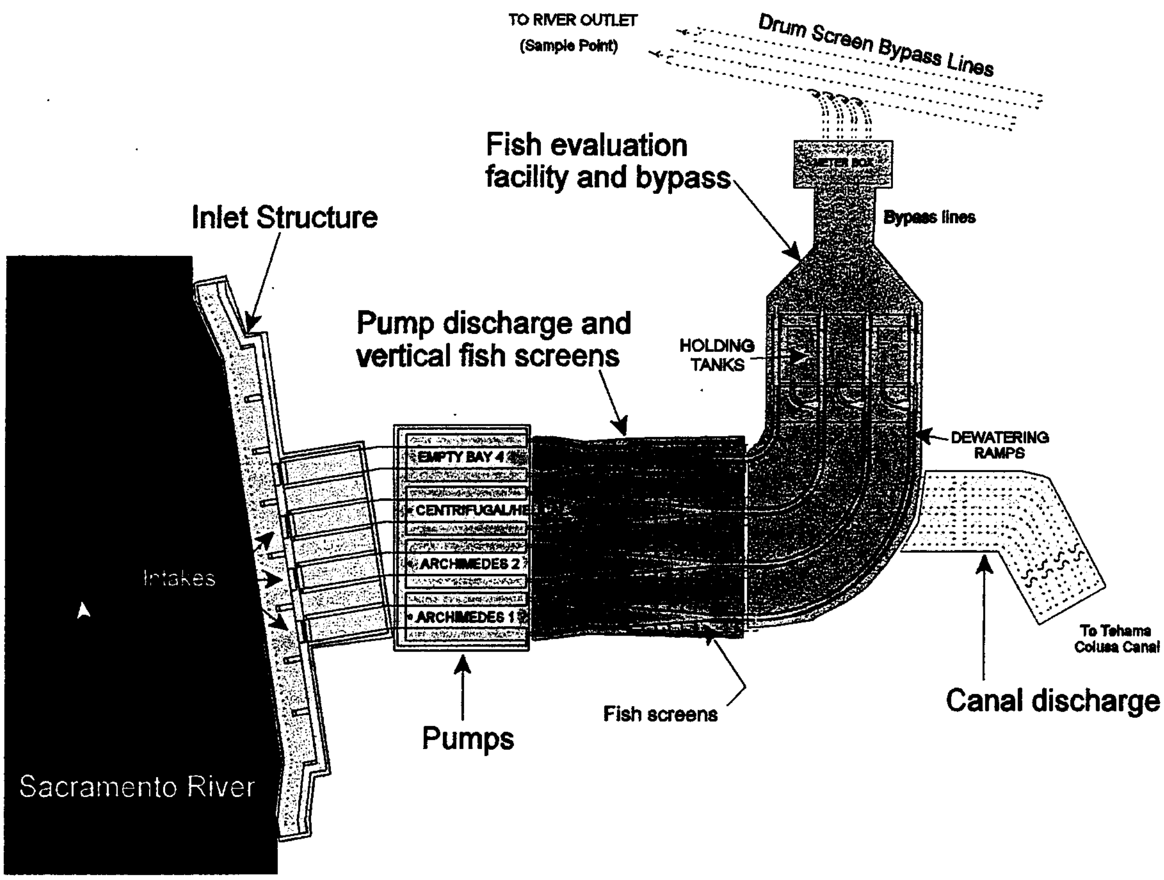


Figure 1. Schematic of the engineering study areas, RBRPP. *Major study areas for the engineering evaluation at Red Bluff Research Pumping Plant.*

The Sacramento River

Background and Previous Studies

The Sacramento River is the longest river in California, flowing some 380 miles from near Mt. Shasta down to its confluence with the San Joaquin River. A large delta is formed as the two rivers combine and flow out through the San Francisco Bay to the Pacific Ocean. The Sacramento supports four separate runs of chinook salmon, with the winter-run being listed by the Federal government as an endangered species in 1993. The completion of the Shasta Dam in 1945, near Redding (about 40 miles north of Red Bluff), effectively blocked the migration of anadromous fish from the upper reaches of the Sacramento and many tributaries. Since that time, the Keswick Dam (completed in 1950) and the Red Bluff Diversion Dam (completed in 1964) have presented additional barriers to fish passage. In addition to the fish passage issues, the nature of the river below Shasta Dam changed dramatically. Flows in the river below Shasta are now dominated by operational releases at Shasta and Keswick, resulting in lower peak flows than were common in the first half of the century, figure 2.

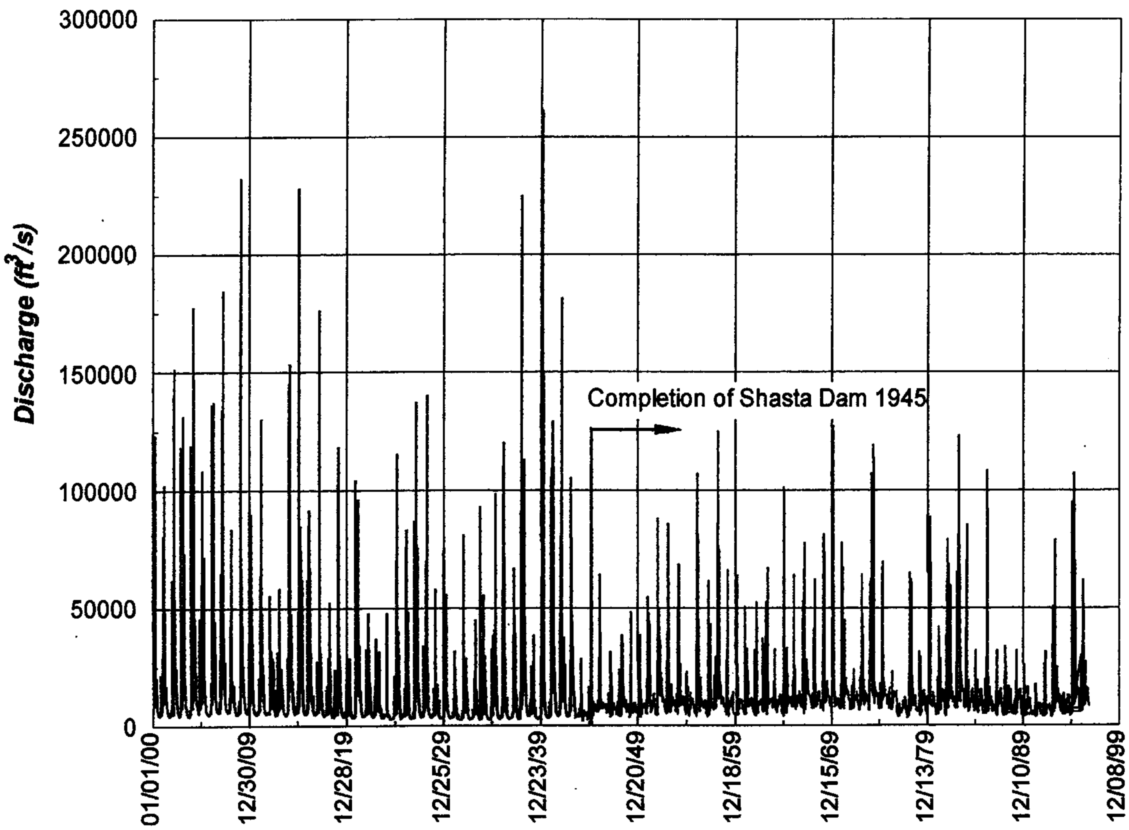


Figure 2. Historical hydrograph at Bend Bridge. *Flow records from the USGS gaging station above Bend Bridge near Red Bluff since 1900.*

The maximum discharge for the period of record was 291,000 ft^3/s on February 28, 1940; since regulation by Shasta Dam began in 1943, the maximum discharge has been 170,000 ft^3/s on December 22, 1964. During the period of our evaluations, beginning in 1995, the area has experienced what would be called average to wet years. This is especially contrasted with the period of drought in the late 1980's to early 1990's, figure 3.

The period of rainfall is generally in the winter months, with almost all the yearly rainfall occurring between November and March. This corresponds to the periods of high flows in the river. The major impact of high river flows on the evaluations at RBRPP is that the bypasses must be closed when the river is above elevation 245 ft at the pumping plant, to prevent flooding of the plant. This river elevation corresponds to a flow of about 40,000 ft^3/s. During the period of evaluations discussed in this report, 5/95 to 10/98, the plant has been unavailable for evaluation due to high flows 8.5-percent of the time (based on average daily flows).

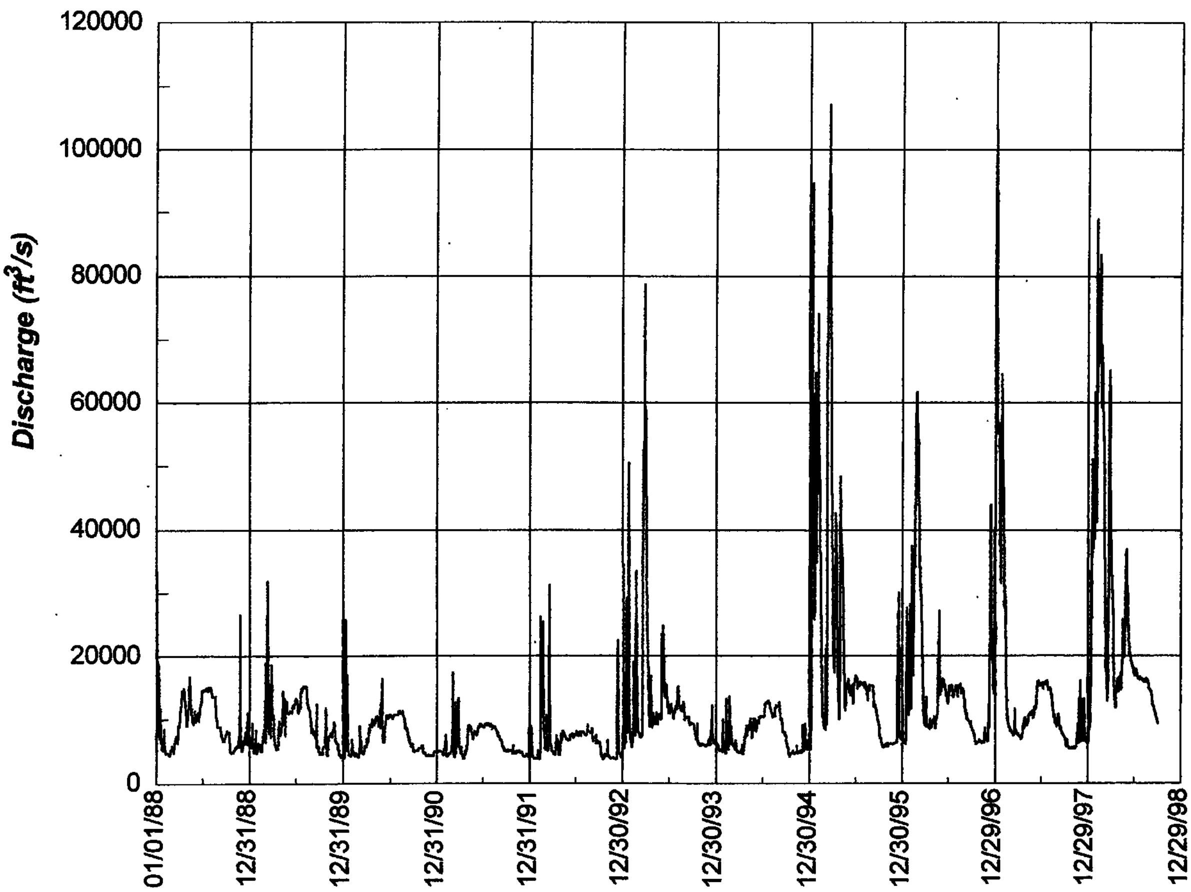


Figure 3. Flow in the Sacramento near Red Bluff 1988-1998. *Recent hydrograph of the Sacramento River at Bend Bridge, above Red Bluff, CA based on USGS gaging station records.*

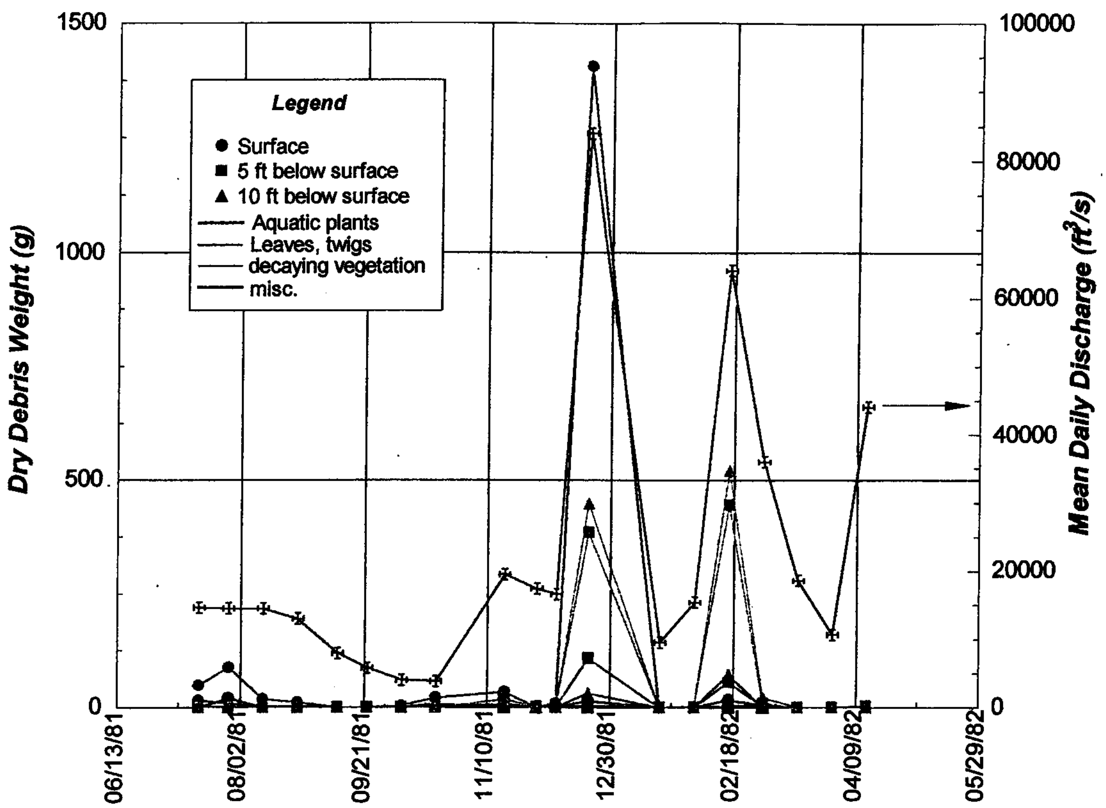


Figure 6. 1982 Debris Study. *Results from one year of data collection on type, quantity, and distribution of debris in the Sacramento River at the Tehama-Colusa canal headworks.*

least surface samples after mid-December 1981. Results show that debris loads are a strong function of river flow during storm events. Debris loads increase with large flow events but tend to drop off after a period of time even if the flows remain high, indicating a flushing effect. Leaves and twigs dominate the surface collection, while decaying vegetation makes up most of the subsurface debris. This study did not quantify large debris such as branches and logs. Many factors affect the debris load, including peaks and durations of flood hydrographs and weather conditions affecting aquatic and terrestrial plant growth. Results from a study such as this have to be interpreted carefully due to debris load being an unknown function of so many different variables.

Model Study and Field Measurements. Operations, sedimentation, and hydrology all have impacts on flow patterns and currents in the river, and in turn, appropriate siting of the RBRPP or any future larger pumping plant. To help site the research pumping plant, preliminary studies were performed in Reclamation's hydraulic laboratory in Denver, Colorado using a 1:36 scale model [Johnson and Campbell, 1993]. The model included the diversion dam and fish passage facilities, and 900 ft of river downstream from the diversion dam. The goal of the model tests was to determine the angle and position of the intake structure to encourage good sweeping flow conditions along the entire structure, even at low river discharges. In addition to the model studies, field velocity

Sedimentation Studies. Sedimentation studies on the Sacramento River at and near the RBRPP site have been performed by Reclamation and the U.S. Geological Survey (USGS). Sedimentation issues with the construction and operation of the Red Bluff Diversion Dam forced Reclamation to perform both suspended and bed-load sediment measurements. During normal river flows where releases are controlled at Shasta Dam, the sediment loads in the river are typically small. However, during storm events when the tributaries between Shasta and Red Bluff are flowing, a substantial amount of suspended and bed loads can be generated. Concerning performance of the RBRPP, the most notable of the tributaries is Red Bank Creek, a tributary whose confluence is directly above the Tehama-Colusa Canal headworks, figure 4. Suspended sediment concentrations of 12,000 mg/l have been

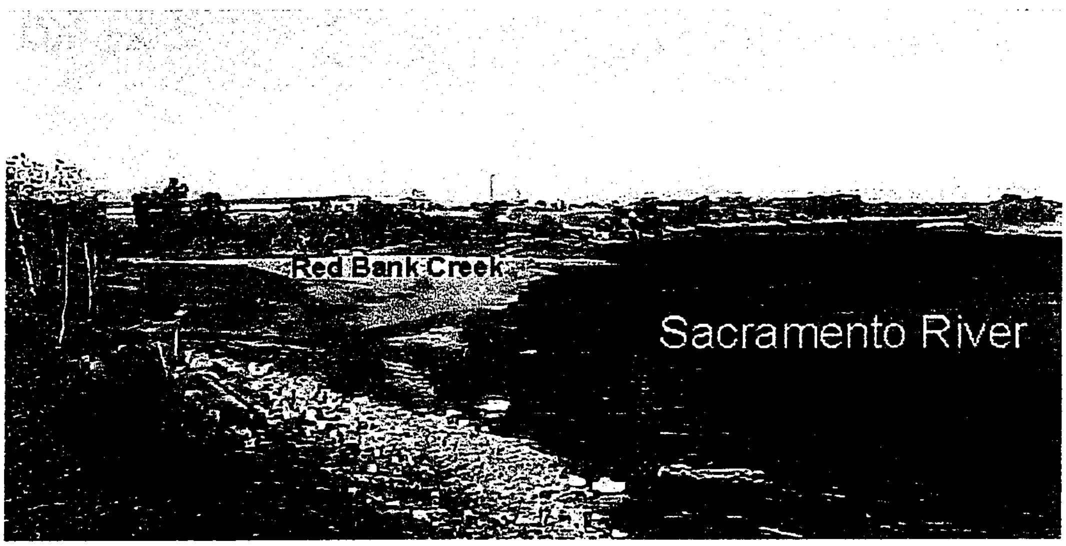


Figure 4. Confluence of Red Bank Creek with the Sacramento River. *Red Bank Creek flows into the Sacramento just upstream from the Red Bluff Diversion Dam above the TCC headworks.*

measured in Red Bank Creek. The mean annual sediment load of Red Bank Creek was calculated to be 1.8 million cubic feet [Blanton, 1991]. The suspended sediment data presented in figure 5 were taken from data published by USGS. The average suspended gradation is plotted on this figure. Pre-1967 data are from Bridge 99E near Sta. 187+30, and samples taken in 1967 were from Bend Bridge, about 16 miles upstream from RBDD. The bed material samples were taken by Reclamation in 1970 from various locations in the Sacramento River above the RBDD. These samples were taken by divers. An average size analysis was computed for all samples, and is also presented in figure 5.

Debris Studies. There has been at least one previous documented debris study at the site of RBDD [Baughman, 1982]. In this study, data were gathered on the type, location in the water column, and quantity of debris which was clogging the traveling screens and louvers at the Tehama-Colusa canal headworks. Data were collected over the period of one year, allowing seasonal variation in quantity and dominant variety to be examined. In addition, data on debris load, as it varied with water depth in the river in front of the traveling screen was also obtained. Debris samples were collected from the river in front of the traveling screens at 2-week intervals for about 1 year.

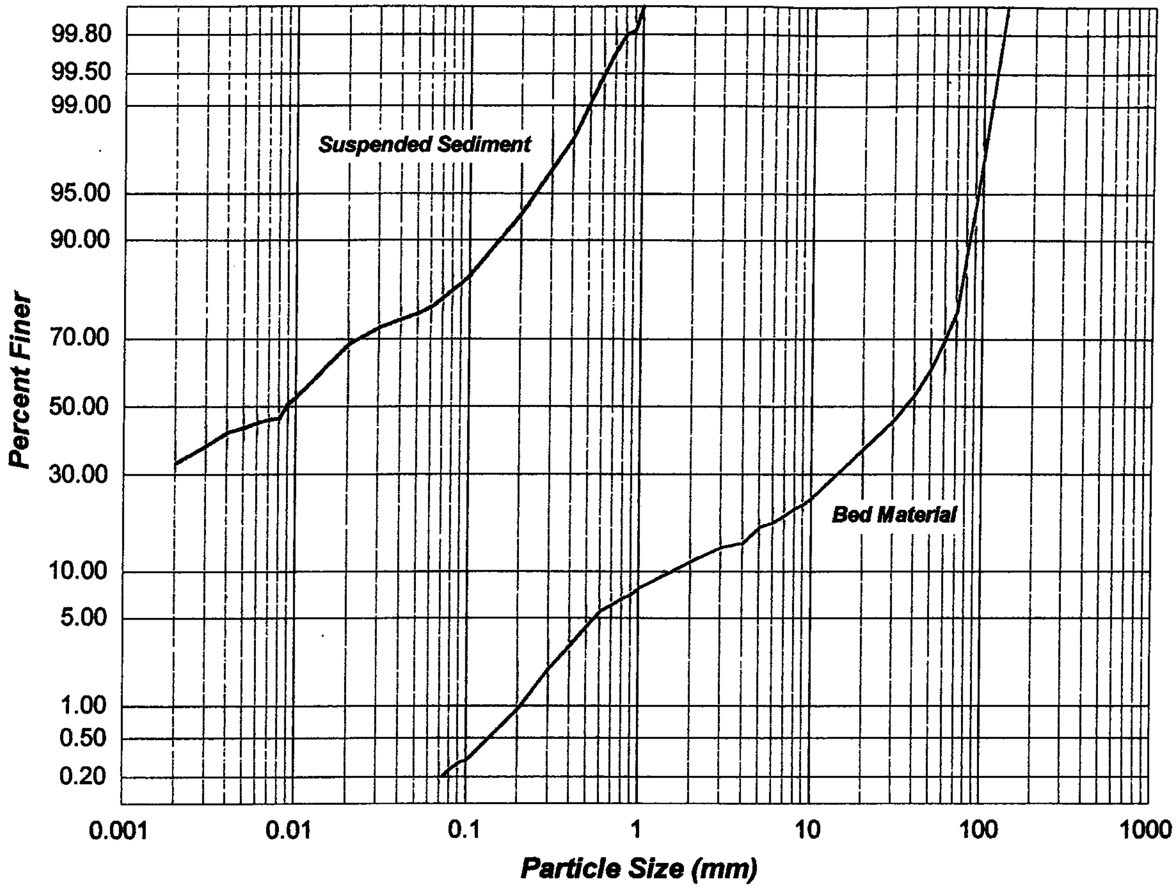


Figure 5. Average Sediment Gradations. *Average sediment gradations, suspended and bed load, taken in the area upstream from Red Bluff Diversion Dam.*

Plankton nets (505 mesh) were used to capture debris. The nets were fitted with current meters, allowing an estimate of the volume of water filtered to be calculated. River samples were collected at intervals in the water column, including surface, 5 ft below surface, and 10 ft below surface. The nets were deployed simultaneously using a truck mounted crane. The normal sampling period was 30 minutes, but varied with debris load. At the end of the sampling time, the nets were raised and the contents washed into the cod-end bag from the outside using river water. The bag was unzipped and the contents washed into sample jars which were placed on ice.

Laboratory analysis of the debris samples included separation into four groups: 1) terrestrial leaves - twigs, stones, etc, 2) non-decaying aquatic vegetation (except algae) - Elodea, etc., 3) decaying vegetation, 4) miscellaneous - aquatic insects, trash, etc. Following the separation, each sample was drained and weighed. The samples were then dried in a 120-degree C oven overnight and weighed to determine dry weight. Figure 6 shows the variation in debris type and position in the water column throughout the study period. Also plotted on the figure is the mean daily discharge of the river at Bend Bridge for the dates sample collections were made. Part way through the year, a log boom was installed to deflect surface debris away from the sampling area and undoubtably had an effect on at measurements were also collected in February 1993. This velocity set included a river section above Red Bank Creek, readings at the centerline of each of the open RBDD gates, a river section 800 ft downstream from RBDD, and a grid of points in the vicinity of the proposed pilot plant intake site. The hydraulic model was calibrated by setting a scaled flowrate of 6000 ft^3/s and adjusting the inflow distribution in the model to generate the field-measured velocity distribution at the dam gates. The velocity distribution at the section 800 ft downstream from RBDD was then measured in the model. Model results were in good agreement with the field measured distribution. This low river discharge was then used to evaluate sweeping flow conditions at proposed alignments of the intake structure. A modification to the initial design configuration was recommended from the model studies. The structure was pushed further into the river channel and the downstream end was also rotated into the flow. Even with these modifications, with a gates up operation at RBDD and low river flows (figure 7) – such as was tested – sweeping flows of less than 1 ft/s were all that could be maintained. With gate manipulations, sweeping velocities could easily be increased to 2 ft/s, however, gate control from Sept.15 to May 15 is currently prohibited by NMFS.

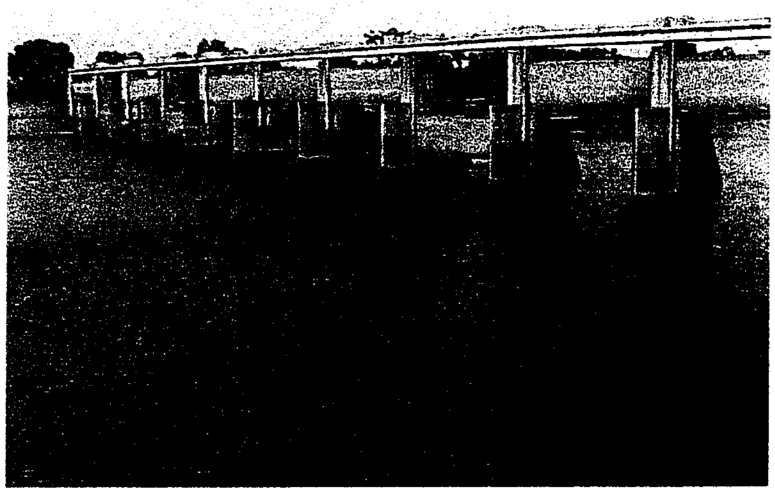


Figure 7. Typical gates up operation at RBDD. *Gates at RBDD are pulled out of the water from Sept. 15-May 15 to allow unhindered fish passage for endangered winter-run chinook salmon.*

At the time of the field and model measurements to site the intake structure, a significant sediment bar extended from Red Bank Creek through the RBDD and angled toward the drum screen bypass outfall structure. This bar effectively guided flow away from the RBRPP intake, especially at low river discharges. During high flow events in early 1995, the bar was breached and sweeping conditions improved at the intake structure.

Current Evaluations Associated with RBRPP

Since construction of the research pumping plant, in-river evaluations have been limited to two velocity surveys. These surveys were performed by Reclamation, using a boat-mounted acoustic doppler current profiler (ADCP) manufactured by RD Instruments, with 600 kHz transducers. Personnel from Reclamations' TSC and MP Region's NCAO participated in the data collection.

Data Collection July 1995. The first data collection trip is detailed in Reclamation Travel Report dated August 14, 1995 by Tracy Vermeyen, D-8560. This first trip was during the "gates in" period, so Lake Red Bluff was established upstream from RBDD. Seven transects of velocity and bottom information were collected upstream from RBDD. One river transect downstream from the diversion dam was measured; however, additional transects were not possible due to shallow water depths. Transects were mapped using a global positioning system (GPS) receiver. Depth-averaged velocity vectors show general flow patterns in the river upstream from RBDD, figure 8.

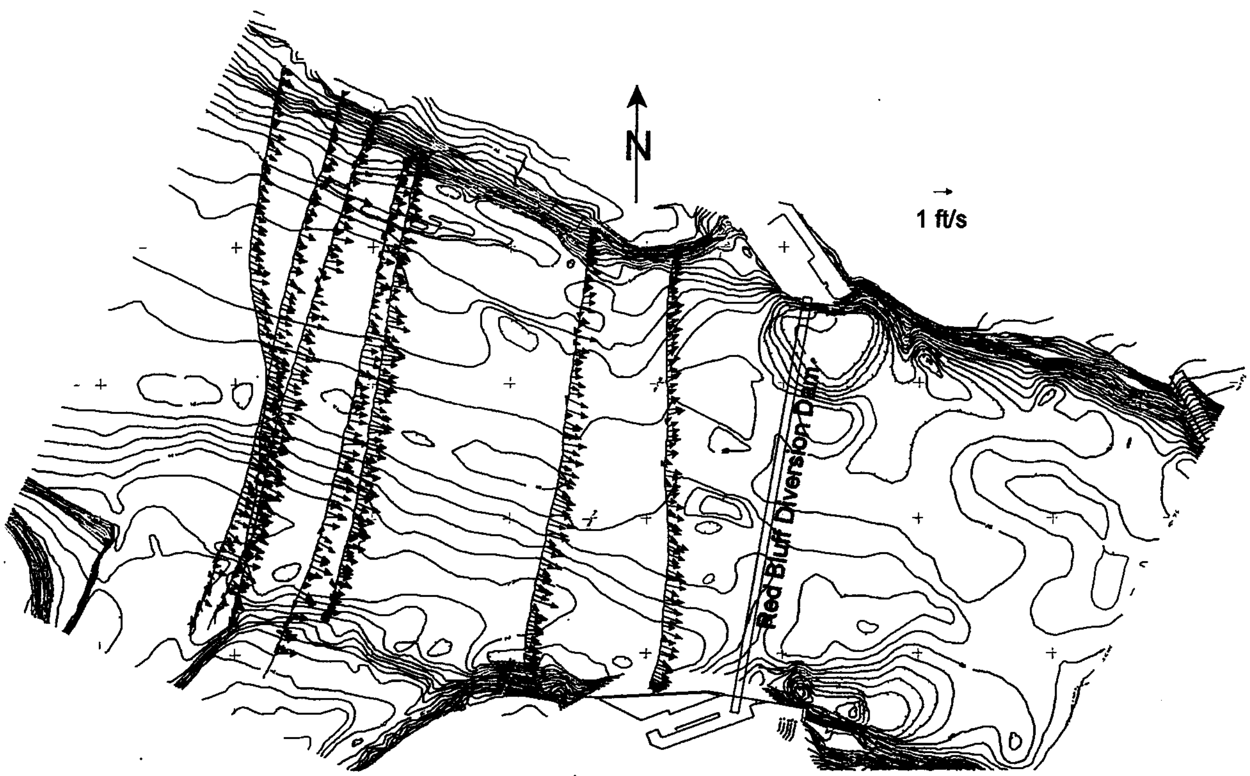


Figure 8. ADCP velocity transects upstream of RBDD. *Depth averaged velocity profiles upstream from Red Bluff Diversion Dam. Acquired by boat-mounted ADCP in July 1995, gates in, Lake Red Bluff in place.*

Transect No. 1 is located about 800 ft upstream from RBDD and shows a fairly typical velocity distribution for open channel flow. As you approach the diversion dam, the velocity profile becomes skewed, influenced by nonuniform gate operations. Throughout the testing, flows were passed through gates 1, 2, and 3 (near the left bank) and through gates 9, 10, and 11 (near the right bank). The fish ladders on both banks were also in operation. The mean daily river discharge on the day of the testing (7/19/98) was 15,800 ft^3/s, reported at the Bend Bridge USGS gaging station. The average discharge measured by the ADCP was 16,100 ft^3/s, a difference of 1.9-percent.

Additional velocity measurements were performed in the vicinity of the RBRPP intake structure. During the measurements, no pumps at the RBRPP were operating. General characteristics show that the sweeping velocity (parallel to the inlet structure) at a point about 10 ft off the trashracks, increased from 2- to 5-ft/s from the upstream to downstream end of the structure. Approach velocity components (normal to the structure) at this location showed low velocities (<1 ft/s) over the first two-thirds of the structure, increasing to 2- to 3-ft/s over the downstream one-third of the structure. This increase in normal velocities indicates a flow into the inlet structure which must exit over the last one-third of the inlet structure.

Data Collection March 1996. The second data collection trip was during March 1996 with a "gates up" configuration (no Lake Red Bluff). This trip is detailed in a Reclamation Travel Report dated April 15, 1997 by Tracy Vermeyen, D-8560. The river discharge as reported at Bend Bridge was 11,200 ft^3/s. Low river discharges and about a 10 ft lower water surface elevation in the river upstream from the dam precluded a complete repeat of all the transects which had been previously measured. Transects were collected at sections 1 and 2, which are 800 ft and 700 ft upstream from RBDD respectively, using a GPS to relocate positions from the July 1995 data collection. Collection of a river transect downstream from RBDD was not possible due to the shallow depths. Comparison of bottom profiles from the 1995 data set showed some local aggredation which would be consistent with the wash out of the bar emanating from Red Bank Creek.

Measurements about 10 ft in front of the intake structure were collected for four different flow conditions in the pumping plant; no pumping, Archimedes 1 pumping 93 ft^3/s, Archimedes 2 pumping 93 ft^3/s, and combined pumping of Archimedes 1 and 2 of 185 ft^3/s. At the no pumping condition, results were similar to those mentioned in the previous measurements (July 1995), with significant inflow at the upstream end of the structure and outflow at the downstream end of the structure. The mid-section of the inlet structure shows almost no inflow to the structure and a consistent sweeping velocity of about 2.5 ft/s. Due to the concentrated outflow from the structure at the most downstream inlet panel, the sweeping velocity component drops to below 1 ft/s out in front of that panel. No significant differences were noted when the various combinations of pumps were tested. The only measurable finding was that there was an increase in the sweeping flow magnitudes along the structure, in particular at the most downstream inlet section, resulting in an increase in the sweeping flow magnitudes to 2- to 3-ft/s.

Positioning of the inlet structure, storm events, and pumping influence the performance of the inlet structure. The magnitude of the pumped flows do not appear to have a significant impact on the general river flows in the near vicinity of the structure. Some localized flow effects including formation of swirls and vortices are dependent on RBRPP pumping.

Inlet Structure

Background and Design

The inlet structure interfaces the research pumping plant with the Sacramento River. In addition to being an inlet, it also doubles as a pump sump. It features a concrete structure placed between sheet pile walls, figure 9. Steel trashracks cover 160 ft of the inlet structure with sixteen 20-ft-wide by 11-ft-high panels. Two panels are stacked creating lower and upper trashracks. Each panel sits at a 1 on 4 slope and features ½-inch wide trash bars with a 2½ inch open spacing between bars. The trash bars are angled at 45-degrees with respect to the lateral support members, figure 10. Prior work has shown that angled bars on trashracks have been effective at maintaining strong sweeping flows into a structure, [Copeland, et al., 1981]. The racks may be arranged so that the bars are angled into the flow or flipped so that the bars are angled away from the flow. Initial settings had the first 3/4 of the panels angled upstream, into the flow, and the last 1/4 of the panels angled downstream. This original configuration was arrived at based on the desire to keep a good sweeping flow component through the structure itself. Besides bar orientation, 18-inch-high solid plates are available to bolt onto the trashrack face, effectively blocking part of the area. The original thinking was that these plates could be placed low at the bed level to preclude sediments from moving into the structure as bed load or high on the racks to help deflect large floating debris from hanging up on the trashrack.

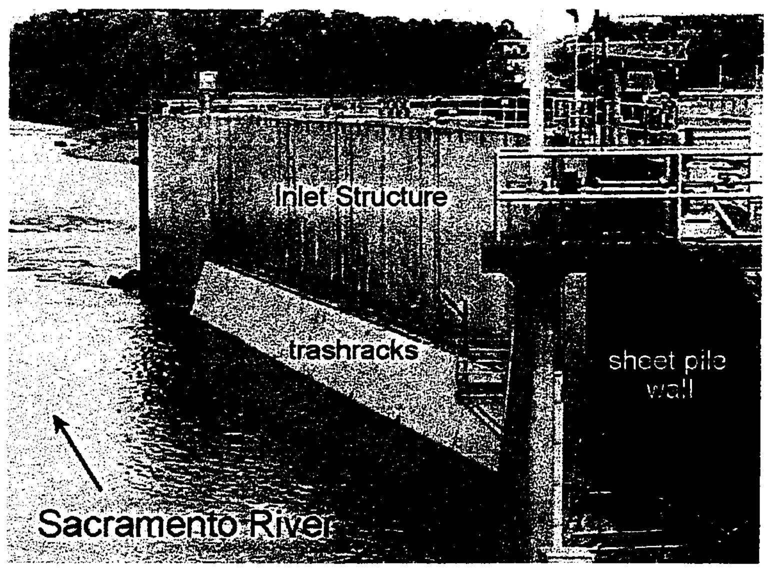


Figure 9. Inlet structure including trashracks. *The inlet structure to the RBRPP includes 160 ft of trashracks with 45-degree angled bars with 2½ inch openings.*

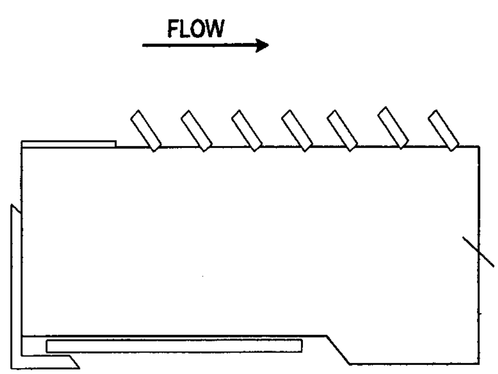


Figure 10. Detail of angled trash bars. *Trash bars set on a 45-degree angle to the trashrack frame. Bars angled into the flow (upstream).*

Each pump intake features a circular bellmouth entrance reducing from a 102-inch-diameter to a 48-inch-diameter. A 1/4-inch steel plate rolled on a 2 ft radius forms the bellmouth adapter that attaches to the 48-inch diameter pipe leading to the pumps. Approximately 50 ft of 48-inch pipe connects the bellmouth adapter to the pump inlets. Each leg of intake piping features a 9-degree horizontally mitered bend. This adjustment was made to allow the entire intake structure to be rotated more into the flow in the river in order to capture more flow and induce higher sweeping velocities past the intake structure. This angle was developed through scale model tests in Reclamations' Technical Service Center hydraulic laboratory [Johnson and Campbell 1993].

Historically, pumping plant inlet structures located on river banks have been designed for a variety of site geometries and plant configurations. The designs are typically very site-specific in their layout, depending on their placement and river conditions. Most references tend to recommend scale model studies to determine proper siting and design characteristics for on-river intakes. While the flow conditions at the inlet structure were studied in a scale physical model, the details of the structure/sump were not studied in these tests. The RBRPP inlet structure also doubles as the sump for the three pumps. According to the *Hydraulic Institute Standards* [1982], the sump volume is only about one-third as large as it should be based on maximum pumping capacity (3 pumps). Typically, off river pumping either incorporates a structure in the river to maintain the gradient and help establish proper inflow conditions or the inlet leads to a larger basin or sump area where sedimentation can occur and pumping conditions can be improved.

Current Evaluations

There have been limited evaluations and changes to the inlet structure. Some problems associated with sediment deposition in the inlet structure have occurred since construction, in particular after large flow events. The initial settings of the angled trash bars on the upstream portion of the structure provided good flow into the structure as evidenced by our ADCP measurements, however as a down side to this, sediments were also readily introduced to the structure. Inspections of the inlet sump by divers revealed large amounts of sediments deposited behind the trashracks. The sediments were mostly sizes of <1-inch in size. There is some evidence that the small gravel and fines move through the pumps into the screening and evaluation structures. However, an equilibrium level of sediment in the inlet structure is reached fairly rapidly.

The trashrack orientation has been changed once since the initial conditions. All of the racks were oriented so that the bars were angled downstream, or away from the flow. This orientation makes the trashracks similar to louver lines. Louvers have been used to guide fish away from dangerous flow conditions, such as pumping plants [Bates and Vinsonhaler 1957, Ruggles and Ryan 1964]. In addition to this change in bar orientation, one 18-inch-high plate was bolted on the trashracks at the bottom of the panels. Subsequent operation has shown that sediment deposition continues, maybe even to a greater extent depthwise, due to the addition of this solid plate at the bottom of the structure.

Fish-friendly Pumps

Two different types of pumps were chosen for evaluation at Red Bluff Research Pumping Plant. Initially, three pumps were installed; two Archimedean screw-type pumps with a rotating cylinder and integral helical flights and one centrifugal pump with a single vane shrouded impeller. The Archimedes pumps were manufactured by CPC, a subsidiary of United Filters. The type installed is commonly known by its trade name, Internalift™ pumps. These pumps feature a 10-ft-diameter rotating cylinder with triple-led helical flights continuously welded along the length of the internal surface. The pumps lift water about 20 ft at a 38-degree angle to the horizontal. These pumps have a sealed inlet with a rotating seal to allow for variation in the river water surface elevation (237.0 to 240.5 as per specifications). The Archimedes pump installed in bay 1 runs at a fixed speed of 26.5 rev/min and will be referred to as pump 1. The Archimedes pump installed in bay 2 (pump 2), although physically identical, can be operated at varying rotational speeds, from 1 to 26.5 rev/min, using a variable-frequency drive. The Archimedes pumps are driven by 3-phase, 350 hp induction motors.

The centrifugal pump is designed and manufactured by WEMCO-Hidrostal, a subsidiary of Envirotech. The WEMCO pump has an inlet and discharge diameter of 36 inches and is the largest of its type ever constructed. It features a single spiral impeller cast with a rotating conical shroud. It is installed in bay 3 (pump 3) at RBRPP, and can share the variable-frequency drive with bay 2, allowing an adjustable rotational speed from 174 to 472 rev/min (the maximum pump speed has been reduced to 354 rev/min due to a change in the gear ratio). A 400-hp, 3-phase induction motor is used to power the pump.

Limited studies prior to RBRPP have been conducted to evaluate fish passage through a rotating cylinder Archimedes pump. These studies were conducted by Pacific Gas and Electric Company (PG&E) and the California Department of Fish and Game to evaluate possible use of a rotating cylinder Archimedes pump as part of a fish bypass for PG&E's Potter Valley intake and are detailed in a report, [Week, Bird & Geary, 1989]. The fixed-cylinder style of Archimedes pumps, while available in larger diameters and greater discharge capacities, had not been evaluated for fish passage. The high potential for fish to be wedged between the rotating screw and the fixed cylinder or trough made the fixed-cylinder style Archimedes less likely to pass fish safely. While fish passage studies are limited, mechanical evaluations of Archimedes pumps with a sealed inlet are non-existent. In general, motor-driven Archimedes pumps with the typical reservoir intake condition, have been very reliable mechanically, and have low maintenance costs. These pumps are used extensively in wastewater treatment facilities throughout the world, and can be used to raise storm water, slurries, and all types of liquids laden with solids. The application of the Archimedean pumps at RBRPP requires them to operate over a fairly large range of inlet water surface elevations (specified range 3.5 ft, actual range 7 ft), requiring a sealed intake. The design and performance of the rotating seal are untested, as well as the effect of having a static water level inside the cylinder of the pump.

The Wemco-Hidrostal pump is a centrifugal pump with a single vane impeller. Applications involving fish include pumping live fish between raceways in hatcheries and clearing holds from fishing vessels in port. They have been used in handling very delicate solids, such as tomatoes and other fruits and vegetables. There have been a number of laboratory studies on handling live fish with this style pump [ARL, 1981 and Patrick, 1982]. Studies have shown that mortality and delayed mortality of fishes is definitely a function of the rotational speed of the pump and possibly some function of the actual pump size (previous studies have featured pumps 12 inches and smaller) as well as fish species. Each of these tests has shown mortalities to be in the range of 1.5 to 4 percent. Mechanical evaluations of the pumps have basically been limited to manufacturer's data, and for the size installed at RBRPP, no data exists.

Over the course of the evaluation period covered in this report (1995-1998), the pumps operated rather sporadically due to design flaws as well as installation problems. The total cumulative hours of operation as a percent of the total possible hours of operation vary from about 13 percent for the Wemco-Hidrostal to 22 to 25 percent for the CPC Archimedes pumps, figure 11.

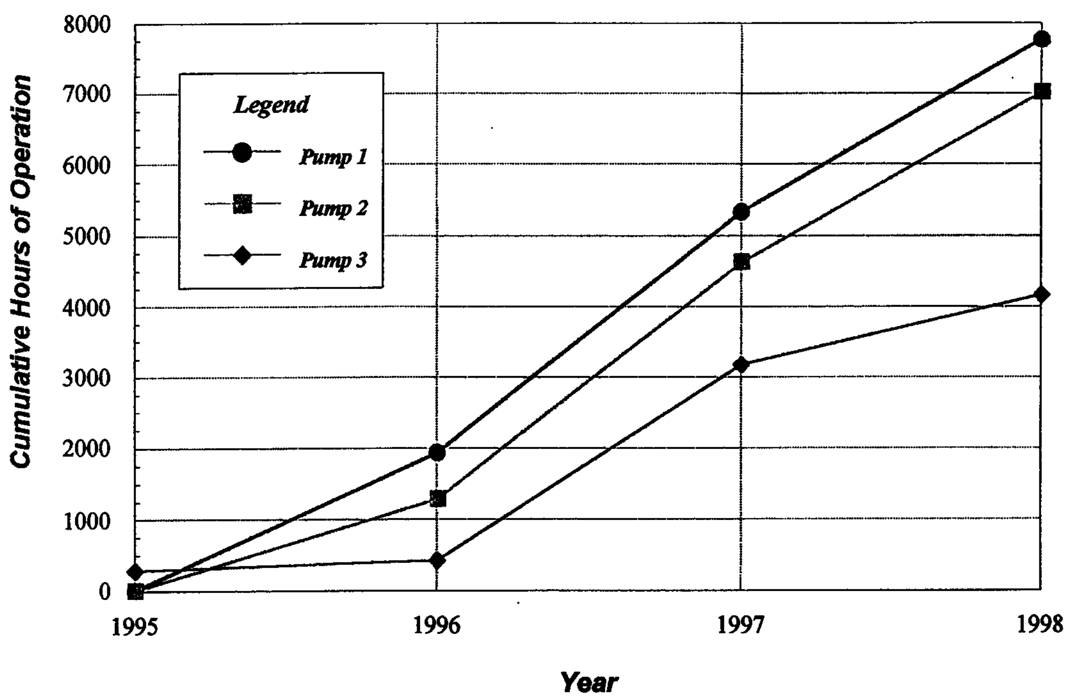


Figure 11. Cumulative hours of pumps operation. *Total cumulative hours of pump operation by year for the period of evaluation, 1995-1998.*

Detailed accounts of required modifications and pump maintenance will be discussed as well as performance and efficiency data. Inlet and outlet conditions and performance will be presented in the specific sections which deal with those topics. Modification history will be presented in roughly chronological order. A tabulated chronology of pump operations and major modifications appears in the appendix.

CPC- INTERNALIFT™ Archimedes Pumps

Operation and Modification History. Installation was completed and operation and subsequent evaluation (both mechanical and biological) of the pumps began on May 2, 1995. Installation was according to drawings and paragraphs in Reclamation Specifications No. 20-C0406 [1993]. A burn-in test was completed with pump manufacturer representatives, contractors, and Reclamation personnel all present. Limited instrumentation was used. The most critical and unproven feature of this pump design and installation was the lower rotating seal. Typically this type of pump is used in an open forebay and operates with a near constant water level, figure 12. However, the RBRPP installation features a sealed intake, figure 13. This was required due to fluctuating water levels in the river and the need to get fish into the pump once they enter the intake area.

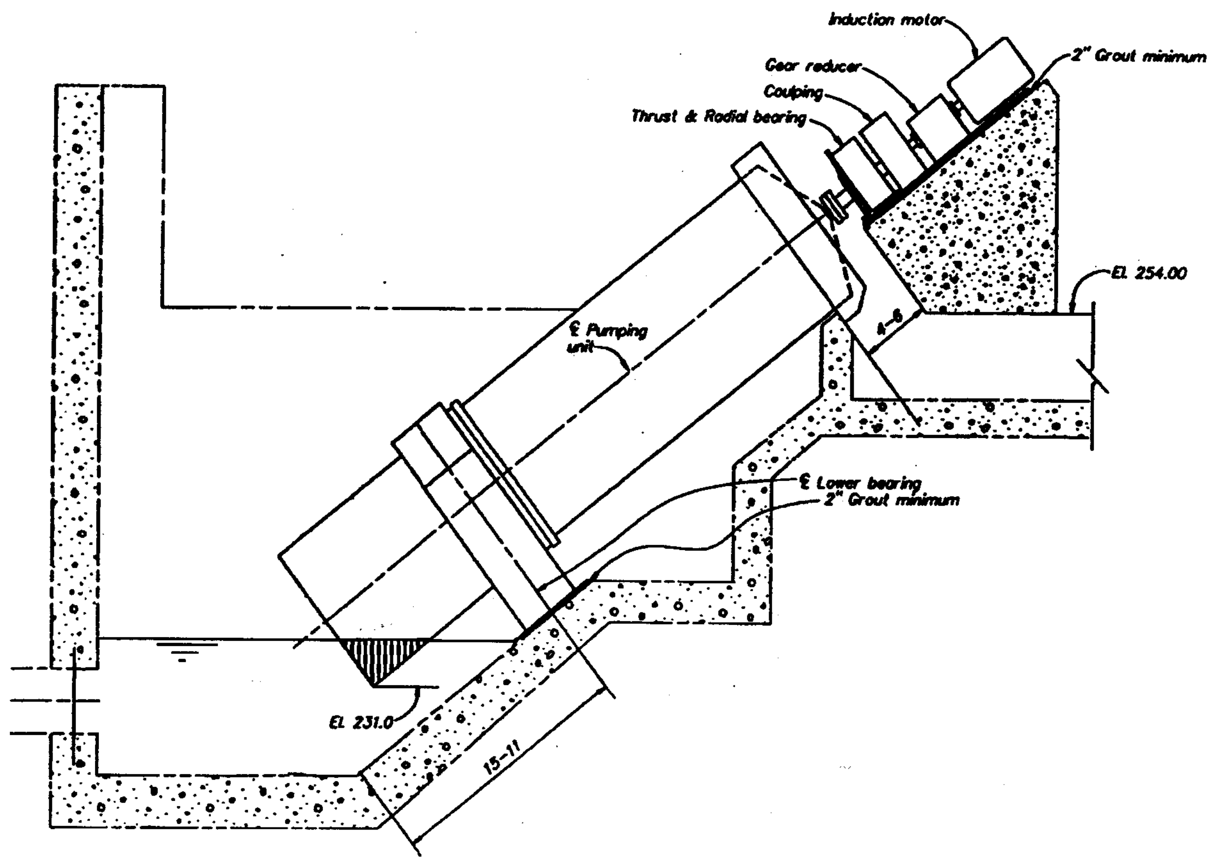


Figure 12. Typical Archimedes Installation. *Typical Archimedes pump installation with open intake from a nearly constant water surface elevation.*

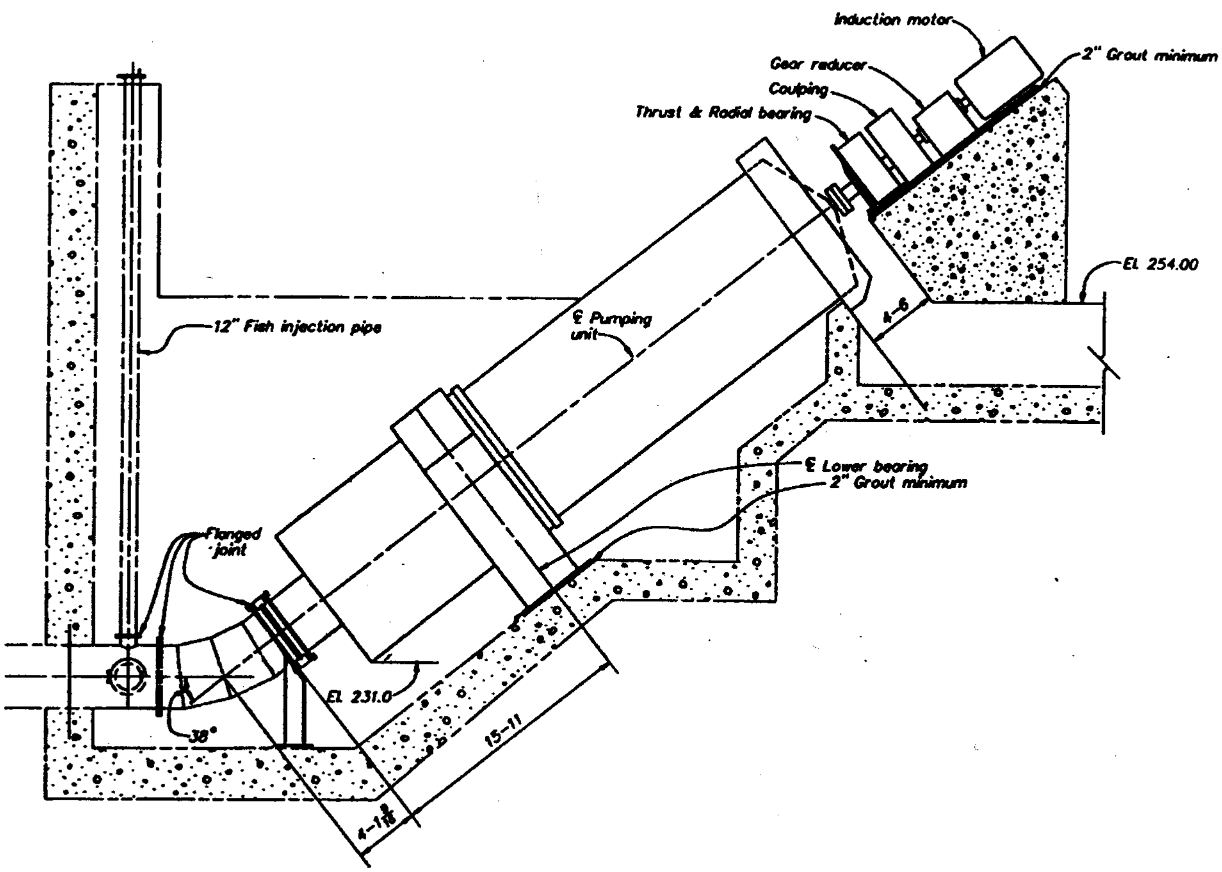


Figure 13. Sealed inlet Archimedes Installation. *Red Bluff Research Pumping Plant installation. Note sealed inlet condition with rotating seal.*

Rotating Seal. Within the 8-hour period of the initial burn-in test, shavings of UHMW (Teflon) seal material (between fixed pipe and rotating pump) were discovered in the discharge channels of the Archimedes pumps, and were accumulating on the wedge-wire screens. Upon closer inspection of the pump, it was determined that sediment from the river was migrating through the packing and lodging between the seal and the fixed roller pipe. This caused the seal to wear excessively. The pumps were shut down and the seal and packing were disassembled. Sediments in the size range of 1/8 inch and smaller had lodged between the UHMW seal and the fixed pipe, causing scoring and excessive wear of the relatively soft seal material, figure 14. Sediment traps were considered as a means to eliminate the sediment from the water prior to entering the intake manifold. This solution was quickly discounted due to the detrimental effects it would have on the inlet velocity and its low probability of success. A redesign of the seal was needed to allow operation with any amount and size of suspended sediments that may be pumped from the river. After several months of unsuccessfully working with the manufacturer to develop a solution without success, Reclamation designers developed a seal which could be manufactured and installed quickly and inexpensively. The seal eliminated large quantities of mechanical equipment and consisted had cracks at three new locations and two cracks at previously repaired sites. The new cracks ranged from 1/4- to 1-1/2-inches long while the repaired cracks were 2-1/2 inches and 10-1/2 inches long. It was decided that any cracks greater than 3 inches would be weld repaired and anything smaller stop drilled, figure 23. It was thought that by stop drilling the smaller cracks, the stresses might have decreased enough and the propagation of the cracks would cease. Pump 2 ran for an additional 863.50 hours before the second inspection. The inspection revealed that there were ten new crack locations throughout the pump and one previously repaired crack 2-3/4 inch long. The new cracks ranged in size from 1/4- to 4-1/4-inches long. The same method of repair was utilized for pump 2.

Figure 23. Stop drill repair on flight crack. *Stop drilling was performed on all new and recurring cracks less than 3-inch long.*

With these repairs completed, the pumps were put back into operation. The pumps were again inspected on April 4, 1997, to determine if the cracking had stopped. Pump 1 had run an additional 874 hours. Three new cracks ranging from 1/2- to 2-inches long were observed. Four of the stop drilled cracks continued to propagate an additional 1/2- to 1-1/4-inch. Pump 2 had 913.50 hours of additional operation before this inspection which revealed continued propagation of eight of the stop drilled cracks. There was new cracking, and all weld repair cracks appeared to be intact. The pumps were immediately returned to service for an additional 1000 hours to determine if the cracking would eventually stop after stress relieving was complete.

On June 4, 1997, the pumps were inspected again. Pump1and 2 had run 951.1 and 907.8 hours respectively, since the last inspection. Inspection of pump 1 showed that six of the previous cracks grew an additional 1/2 to 1-1/2inches and three new cracks of 1/2 to 5inches in length originated. Pump 2 had five new cracks ranging from 1/2- to 3-inches long and eight cracks continued to enlarge 1/4- to 3-inches. The pumps were returned to service to continue critical biological evaluations of the pumping plant facility.

Continued crack formation and propagation led to analytical studies at Reclamation's Technical Service Center. Personnel ran a finite element analysis on the Archimedes pump to determine how the loading at various river elevations affected the pumps. The analysis indicated that the stresses on the pump flights were greater than the structure could support and hence the cracking. Finite element analysis indicted that a reinforcement of the flights was necessary to increase the flight strength. A spiral reinforcement ring 1/4-inches thick, 4-inches wide was installed on each side of the Archimedes flights, a minimum of 2 inches in from the leading edge. The plates were cut and shaped to conform to the existing curvature of the pump. The plates were then welded into place on both sides of the flights. The reinforcement extends from approximately the third flight from the bottom of the barrel up to the drive shaft connection. The reinforcement was completed on September 9, 1997. The pumps were put back into service on September 11, 1997. The pumps were inspected on November 3, 1997, after an additional 1060.7 hours of operation on pump 1 and 1063.25 hours for pump 2. Two cracks of 1-inch and 3/4-inch long were found in pump 2; no cracks were observed in pump 1. The pumps were shut down due to high water on January 7, 1998. An additional 222.6 and 223.8 hours of operation were accumulated on pumps 1 and 2, respectively. An inspection of the pumps was performed at this time and no additional cracking was evident.

The pumps were started again on March 10, 1998, and ran intermittently until July 21, 1998, when the next inspection was performed. Pump 1 ran for an additional 1228.9 hours and pump 2 ran for an additional 1150.99 hours when Reclamation employees performed the inspection. One 3/4-inch long crack was discovered in pump 1 and four cracks were seen in pump 2, two of which had previously been documented. Three of the cracks were 1-1/2-inches long or less and were not a concern. One crack however, was not very long, but appeared on both sides of the reinforcement ring. No repairs were made, and the pump was put back into service. The cracking of the flights has dramatically diminished, and the existing cracks will continue to be monitored to determine if the reinforcement plates continue to withstand the stresses.

Oiling Delivery and Recovery System. An oil recovery system was designed for the lower roller bearings which allows used oil to be captured, filtered, and reused. The original oiling system operated without any capture or reuse components, and 5 to 7 gallons of oil per 24-hour period were used (approximately $100 per day). In addition to the high cost of operation, environmental problems also existed since the used oil could possibly be pumped into the Tehama-Coulsa canal system under certain conditions. The oil recovery system consists of three 35-gallon barrels. The used oil returns from the roller bearing shrouds to the center barrel where the oil separates from the water. The water flows to a barrel that drains to the sump while the oil flows into a storage barrel where it waits to be filtered and reused. The programmable oiling system originally supplied with the pumps was replaced with larger, more reliable components that do not require programming. In addition, the system was automated, no longer requiring twice-daily manual filling of the oilers.

Wemco-Hidrostal Centrifugal/Helical Pump

Operation and Modification History. Operation and evaluation of the pump began on May 22, 1995. Installation was according to drawings and paragraphs in Reclamation Specifications No. 20-C0406 [1993]. An elevation view of the pump bay installation is shown in figure 24. The Wemco-Hidrostal is a centrifugal-type pump with a single vane helical screw impeller. Flow enters the pump horizontally and exits vertically, figure 25. A burn-in test was completed with pump manufacturer representatives, contractors, and Reclamation personnel all present. Limited instrumentation was used. Initial operation was very smooth. The pump delivered 110 to 115 ft^3/s at maximum speed, (378 rev/m). With the Archimedes pumps shutdown for redesign of the rotating seals, the

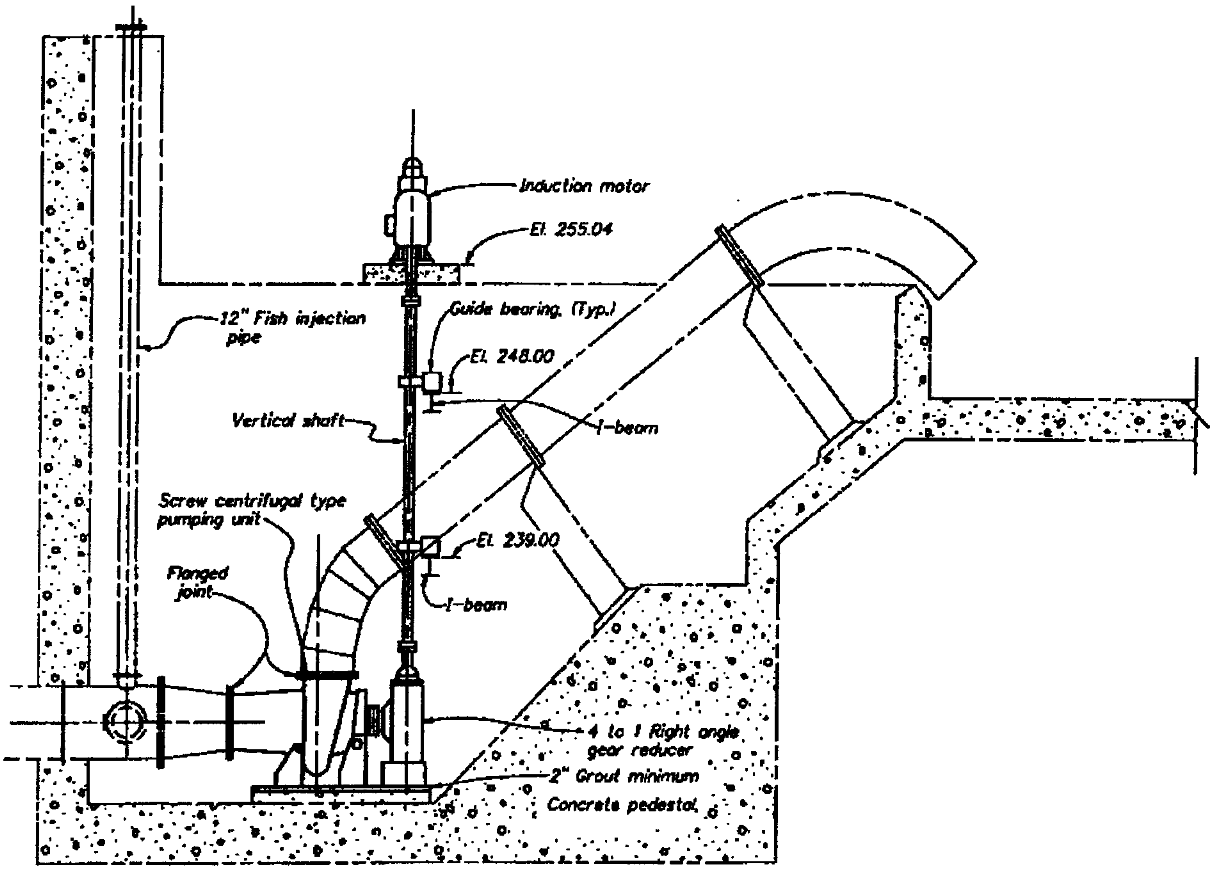


Figure 24. Wemco-Hidrostal centrifugal pump installation. *The Wemco-Hidrostal centrifugal pump installation at Red Bluff Research Pumping Plant*

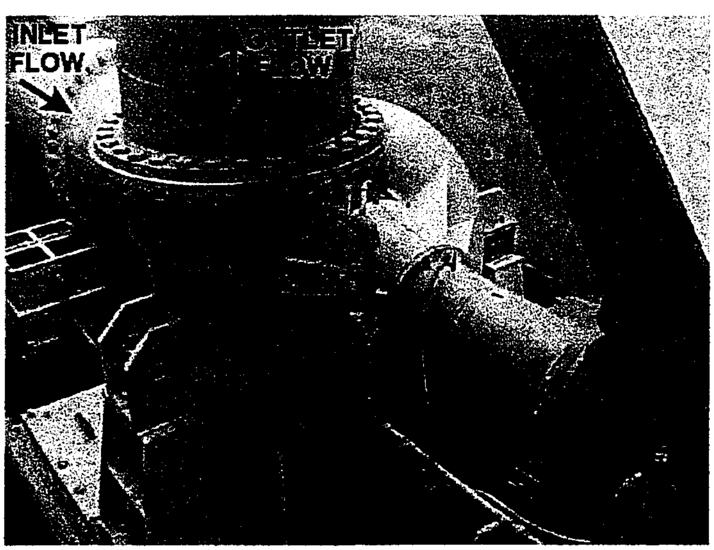


Figure 25. Flow path through the Wemco-Hidrostal Pump. *This photo shows the flow direction in the Wemco-Hidrostal (36X36) pump installed at RBRPP.*

centrifugal pump was used to begin the biological evaluations. The pump operation was initially very smooth; however, over the course of only 254 hours, shaft runout and pump noise forced the pump to be shut down on September 14, 1995. Upon inspection of the pump, it was discovered that the impeller had shifted radially along the pump shaft impinging the impeller on the intake manifold. A broken shaft had caused the pump to seize, figure 26. The impeller was shipped to the manufacturer's plant in Salt Lake City, UT, where it was discovered to be extremely out of balance. A new shaft was manufactured in Peru and shipped to the Utah facility where the impeller-shaft assembly was dynamically balanced, requiring welding over 100 lbs of steel plates to the interior and exterior surfaces of the impeller, figure 27.

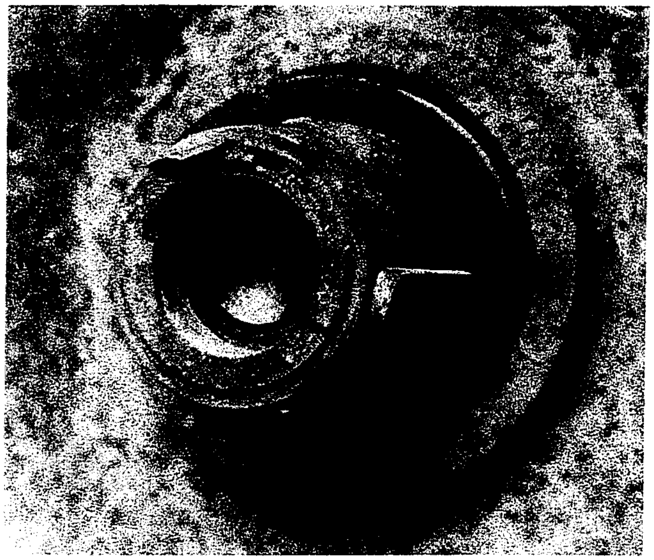


Figure 26. Broken shaft on Wemco pump. *First occurrence of broken shaft, likely due to fatigue damage.*

The pump was re-started on July 23, 1996, and ran intermittently for 141.5 hours, until September 3, 1996. Throughout this period of operation, the pump had been experiencing a hydraulic imbalance, most likely caused by the balancing weights that were added to the exterior of the impeller. Pressure fluctuations of about ± 20 lb/in^2 were recorded in the pump casing . Noise and vibration increased in intensity with the number of hours of operation. Towards the end of this operational period, packing material began shredding and appearing in the stuffing box area. The manufacturer concluded that the hydraulic loading was too great, and decided to cast a new impeller which could be dynamically balanced without adding extra material to the casting.

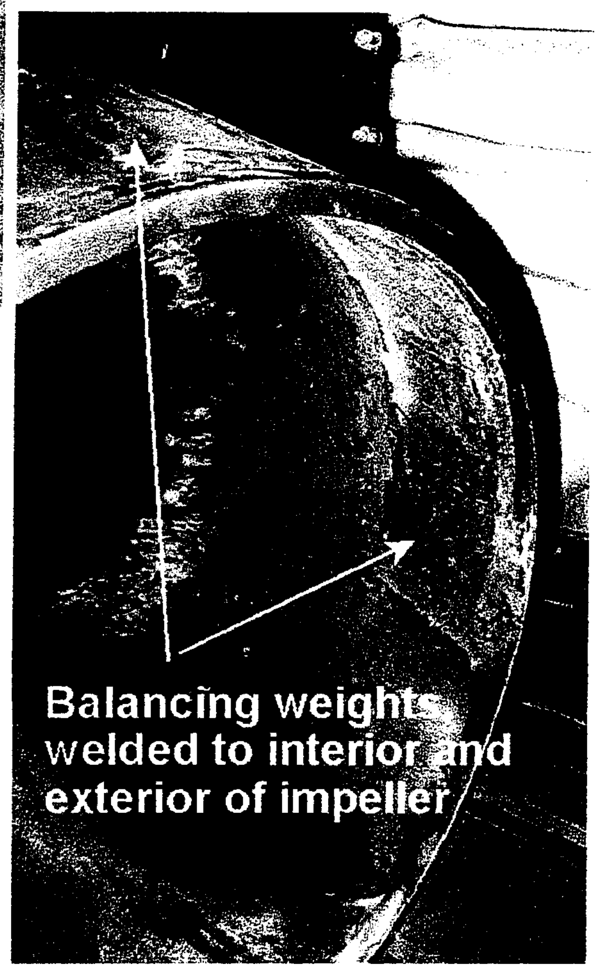


Figure 27. Balancing weights added to Wemco impeller. *Steel plates were welded to the interior and exterior surfaces of the impeller to allow dynamic balance.*

The pump was re-assembled and operational on February 3, 1997. Pump noise, vibration, temperature, and shaft runout (0.020 inch) were all monitored and were within the manufacturers' specifications. The pump ran until early March 1997, logging 547 additional hours of pumping. The runout of the shaft had been gradually increasing and noise from the pump continued to increase. Inspection of the pump once again revealed a broken shaft and significant impeller damage as well as damage to the wear ring. A local machine shop machined the impeller to minimize the effects of the damage, a new wear ring was installed in the pump housing and a new shaft was installed in the pump. The pump was operational by March 21, 1997, and ran until April 19, 1997, when a measured runout of 0.47 inch made it necessary to shut the pump down for realignment. Inspection revealed that the pump had vibrated enough to cause the shims to loosen from beneath the bearing housing. The pump had run 570 hours since the last maintenance. The pump was re-aligned by replacing the shims. Pumping continued until July 9, 1997, when runout, noise, and vibration reached a point that could no longer be tolerated. The pump had run 650 hours since the realignment.

The manufacturer decided that a modification was needed to reduce the vibrations. Modifications were made to the bearing housing which included reversing one set of bearings to take thrust load and manufacturing a tapered wedge ring to pull the bearing house in tight into the pump housing during assembly. A new bearing housing was also cast. During the downtime, the cooling water system was modified by Reclamation personnel to prevent the strainers from clogging and shutting off the pump. After all modifications were made and installation complete, the pump was restarted on September 4, 1997. The pump ran for 1035 hours with the new designs in place until a bearing failure occurred on April 30, 1998. On that morning the internal-helical pump was operating at a much higher noise level than usual. Runout measurements were immediately taken on the shaft and ranged from 0.060- to 0.080-inch. The forward alignment bearing temperature was 228 degrees Fahrenheit. The pump was shut down immediately. After consulting with EnviroTech (Wemco) and LMH, Inc., a local company was contracted to disassemble the pump.

On May 4, 1998, the contractor began to disassemble the internal-helical pump. During the disassembly, several observations were made. First, the impeller bolt retaining the impeller to the shaft was loose. The impeller flange, which is located inside the impeller and transfers the rotation of the shaft to the impeller, was also loose and had some damage from wobbling on the drive pins. After closer inspection it was observed that the impeller flange nut was loose and the lock washer holding the nut was not bent against the nut. There was no visible damage to the wear ring or impeller. The bearing housing, impeller flange, and gearbox were shipped by truck to LMH, Concord, CA on May 6, 1998. LMH then shipped the equipment to EnviroTech in Salt Lake City. The manufacturer machined a new shaft and replaced the bearings. The reassembled pump arrived back in Red Bluff in mid-August 1998. Reclamation decided to thoroughly inspect the pump prior to re-installation. The impeller was dynamically balanced from 3.46 mils (starting) to 0.32 mils (completed). The impeller flange was blued to verify at least 80-percent surface contact. It was observed that only point contact was made at the back of the shaft. The bearing housing, shaft, and impeller flange were sent back to Salt Lake City to correct this problem. The manufacturer machined a new shaft with the proper taper and sent the pump back to Red Bluff. The impeller flange was replaced concurrently by LMH due to the wear from the last failure. The pump was pre-assembled and everything fit tight with a 0.0015-inch parallel runout along the shaft.

Reassembly of the pump was completed on September 10, 1998, and baseline testing began the following day. Utilizing the variable-frequency drive, the pump was run empty (dry) at speeds ranging from 127 to 382 RPM. The pump ran extremely smooth at all speeds with very little vibration and with a runout equal to that found during the pre-assembly check. The pump was then watered up and testing continued. As the speed of the pump increased under load, both the vibration and runout increased. Although the vibration and runout increased, Wemco determined that running the pump at a reduced speed, 348 rev/m (55 Hz), was still acceptable. However, running the pump at the full speed of the motor, 60 hertz (379 RPM), nearly doubled the vibration and was not acceptable.

The runout of the pump was 0.011 inch at startup and increased to 0.012 inch after approximately 200 hours. The pressure in the inlet pipe fluctuated ±1.6 ft at a high frequency (probably at the rotational frequency 5.8 Hz). These pressures will continue to be monitored. The bearing temperatures have stabilized and the pump appears to be running smoothly. Currently there are multiple temperature sensors located on the pump and bearings. Installation of proximity sensors, which will monitor runout, will be completed next calendar year. The data taken from the pump sensors is being continually downloaded to the automation equipment and the information can be analyzed for trends to determine if problems are arising.

Pump Performance Data

During the spring and summer of 1998, an automated data acquisition and control system was installed to enable continuous recording of performance and operational data and to allow remote control of the pumping plant. At the time of this report, about 3 months of efficiency and flow data have been collected. In order to present comparative data at this early stage, overall or water-to-wire efficiencies will be presented. The overall efficiency will be determined using:

$$\eta_o = \frac{whp}{ehp}$$

where: η_o= water-to-wire or overall efficiency, *whp* = liquid horsepower, and *ehp* = electrical horsepower. The liquid horsepower and electrical horsepowers are defined as in the *Hydraulic Institute Standards* [1982]. The determination of H, head, in the liquid horsepower computation will be defined as the difference between the river water surface elevation and the maximum possible elevation at the pump delivery point. The overall efficiency is defined as the product of all the component efficiencies in the system:

$$\eta_o = \eta_p \times \eta_m \times \eta_d$$

where the subscripts refer to the pump, motor, and drive pump/coupling. In addition, head losses, including the trashrack, intake, and piping leading to the pump, are lumped into these values. The value of the overall efficiency or system efficiency is typically quite low compared to the pump efficiency alone.

Computation of the system efficiency requires measurement of the suction and discharge heads, flowrate, and power consumption. The suction head can be determined by either of two methods; a gage recording the river elevation feeds into the data acquisition system, or a pressure transducer measures gage pressure at the centerline of each inlet pipe, upstream from the pumps. When computing an overall or water-to-wire efficiency, the river elevation will be used, resulting in hydraulic friction and minor losses being included in the efficiency determination. Currently, no direct measurement of the discharge head is being made, so in order to compute the efficiencies, the following assumptions are made: Archimedes pumps - El. 256.53 ft (elevation at the 1/4 full point of the cylinder) is the maximum lift point used, the velocity head is computed based on the lower 1/4 of the 10-ft-diameter being full, the centerline of the pump cylinder beginning (El. 234.89 ft) is used as the datum; centrifugal/helical pump - mid-point of the diffuser at its highest point (El. 257.43) is used as the maximum lift, velocity head is calculated based on ½ the area of the diffuser; pump datum is El. 230 ft. Flowrate through the pump is calculated by summing the propeller flowmeter on the canal exit line and the magnetic flowmeter on the bypass pipeline. Given the types of flowmeters being used, accuracy of about ±3-percent of the total flow can be expected. The power measurements are being made by the two-wattmeter method, using 2 CT's (current transducers) and 2 PT's (potential transducers). The kilowatts from each current transducer are summed internally to give the total power used by the 3-phase induction motors.

Water-to-wire efficiencies have been calculated for pumps 1 and 3, for the period October - December 1998, figure 28. The pumps were not operated from mid-November thru the end of the year, so the data are limited. Data are stored on a 30 minute interval. Efficiency values are quite low considering typical manufacturer's claims of 90-percent efficiency for the Archimedes pumps and 75-80 percent efficiencies for the Wemco-Hidrostal pump. These claims are of course for pump efficiency only, not including hydraulic, motor, bearing, and drive losses. In addition, for the Archimedes pumps, no data are available for a sealed inlet condition where the suction head is above the lower centerline setting of the pump.

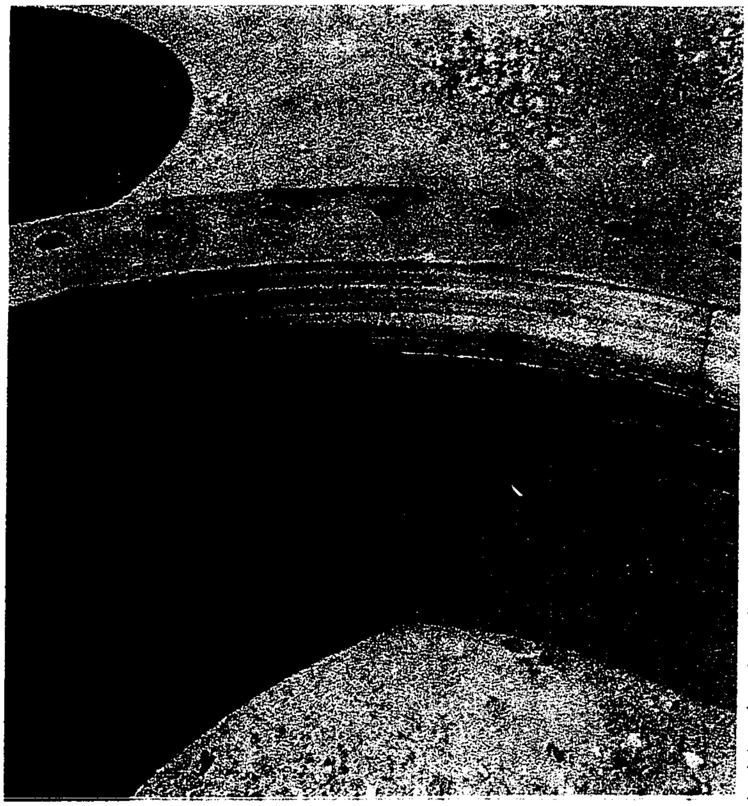
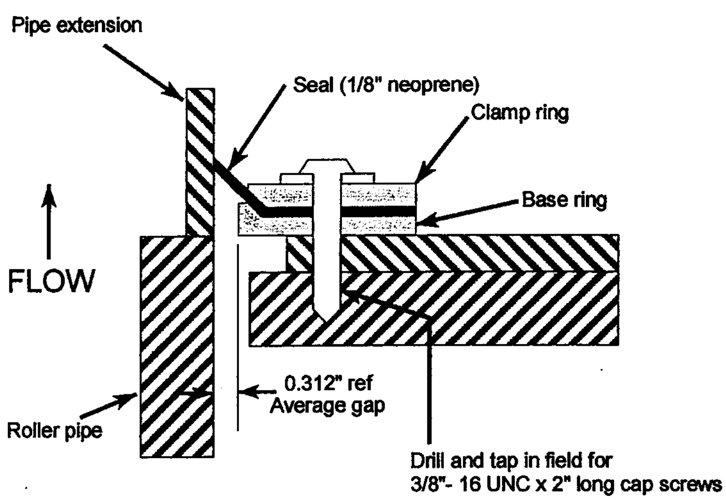


Figure 14. UHMW seal ring. *Wear and scoring on UHMW seal ring on Archimedes pumps, due to sediment intrusion.*

of two brass rings and a rubber seal, figure 15. The seals have performed well with little to no leakage or wear since installation.

Evaluations of the Archimedes pumps began again in March 1996. Emphasis was placed on keeping the pumps running in order to make progress with the numerous planned biological evaluations. Soon after startup, problems arose with the oiling system. Both pumps were fed by a single system and when it malfunctioned both pumps would stop. Initially, programmable circuit boards within the unit were replaced. This seemed to correct the problem, even though both pumps were still tied to a single oiling system. In late April 1996, pump 2 had a failure of the low-speed coupling and had to be shut down.



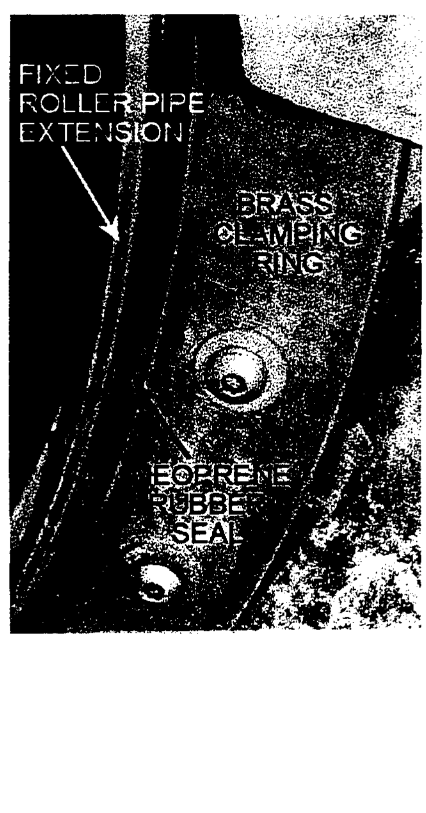


Figure 15. Schematic of modified Archimedes inlet seal. *Detailed schematic of modified rotating seal installed in the two Archimedes pumps at RBRPP, photo shows detail of actual installation.*

<u>*Low-Speed Coupling Failure.*</u> In late May 1996, both pumps were dewatered and a major inspection was performed. The inspection began with the low-speed couplings due to the known failure on pump 2. The low-speed couplings, manufactured by Falk Couplings, are used to couple the gear box reducer to the pump thrust bearing. The couplings used in the Archimedes pumps were model 1000T series tapered grid steel flex couplings with split covers, type T10, size 1200T. The service manual gives the alignment limits for installation of the couplings as a maximum offset of 0.015 inch and within 0.027 inch of angular alignment. Lubrication specifications also require the coupling to be filled with 12.5 lbs of grease prior to operation. Upon disassembly of the unit, it was noted that the coupling cover of pump 2 had a circumferential break between the center coupling fastener and the fastener on the driven side. After removal of the cover, subsequent inspection showed the grid had broken into several pieces, figure 16. Wear marks on the cover indicated that the coupling had broken and was rubbing on the cover. An estimated 1-2 lbs of grease was recovered from the coupling. The grease was very thick and extremely dry. Excessive wear was observed on the hub grid teeth on both the drive and driven hubs. Measurements of the mean tooth thickness for the new coupling had been 0.765 inch on both coupling halves. The measured thickness of the disassembled driven coupling hub teeth was between 0.610 to 0.630 inch and for the drive hub 0.657 to 0.682 inch, indicating a maximum wear of 0.155 inch and 0.108 inch, respectively. The low-speed coupling offset and angularity were then measured. The offset was 0.110-inch top to bottom and 0.21-inch side to side. The face-to-face angularity measurement looking toward the driven unit are given in Table 1. These measurements reflect a maximum angularity of 0.226-inch top to bottom and 0.033-inch side to side.

Figure 16. Damaged low-speed coupling. *Damage to low-speed coupling, Pump 2 (broken grid)*

Position (degrees)	Angularity - face-to-face (in)
0 (top)	0.502
180 (bottom)	0.276
90 (left)	0.375
270 (right)	0.408

Table 1: Face-to-face angularity measurement on low-speed coupling, pump 2.

When the low-speed coupling on pump 2 failed, pump 1 was inspected. It was discovered that it had been operating with a lack of grease in the coupling, resulting in the coupling cover being noticeably hot to the touch. Fourteen pounds of grease was added to the coupling per Falk's requirement, to allow for continued operation of pump 1. After the grease was added, the cover temperature during operation was very close to the ambient temperature. The pump 1 continued to operate, providing supplemental irrigation deliveries through May 16, 1996. Once the gates at RBDD went in, pump 1 was taken out of service, the coupling cover was removed, and the interior was inspected. The grids were broken similarly to pump 2. Marks were present on the inside surface of the coupling cover indicating that the coupling had broken and was wearing on the cover. Wear patterns on the hub teeth were consistent with those seen on pump 2. Measurements taken on the grid hub teeth showed the thickness of the teeth ranged from 0.692 to 0.705 inch on the driven hub and 0.746 to 0.754 inch on the drive, for a maximum wear of 0.073 and 0.019 inches, respectively. The angularity and offset of the coupling were then measured. The offset was 0.077-inch top to bottom. The face-to-face angularity measurements looking toward the driven unit are given in Table 2.

Position (degrees)	Angularity, face-to-face (in)
0 (top)	0.454
180 (bottom)	0.274
90 (left)	0.373
270 (right)	0.354

Table 2: Face-to-face angularity measurements, low-speed coupling, Archimedes 1.

These measurements indicate a maximum angularity of 0.180-inch top to bottom and 0.019-inch side to side. Before any further disassembly was performed, a thorough visual inspection was performed to determine if any component movement could be detected. There was no evidence that anything had moved. Measurements taken on the low-speed couplings during disassembly showed that the difference between the coupling face-to-face distances from top to bottom were 0.226 inch, for pump 2 and 0.180 inch for pump 1. The manufacturer's recommendation for the maximum allowable face-to-face distance was only *0.027 inch* for this size coupling. Both pumps also exceeded the maximum allowable angular alignment limits set by the coupling manufacturer. The base plate for the motor, gear box, and thrust bearing is a one-piece construction anchored with embedded bolts in concrete and the gap underneath filled with grout. There was no visible sign that the plate could have moved the required amount to produce the misalignment measured in these pumps. The lower rollers would have had to be moved down nearly 4 inches to produce a face-to-face misalignment of 0.226 inch at the coupling, also no visible sign of any movement. Inspection of the foundation did not indicate any apparent movement of the structure. The high-speed coupling on both pumps was within the manufacturer's maximum specified limits, indicating there was not movement between the motors and gear boxes.

The low-speed couplings on both pumps were replaced in June 1996. The low-speed and high-speed couplings were realigned by Precision Balancing Service (PBS) using laser alignment equipment. The original alignment was performed using dial indicators. Realignment consisted of adding shims under the motor and gear box. A total of more than ***1 inch*** of shims was needed to bring the motor into alignment. The new couplings were filled with grease as per the manufacturer's installation procedures. The couplings were checked for alignment by PBS after 80 hours of operation and no change in the alignment of the low-speed coupling was found on either pump. Improper alignment and lack of lubrication by the contractor during initial construction caused the failures in the low-speed couplings on each pump.

Thrust Bearings. Due to the failure of the low-speed couplings, other components of the drive train were also inspected. The thrust bearing cover could easily be removed when the low-speed coupling was removed for replacement. The thrust bearings were designed and fabricated by CPC. The thrust bearing is a spherical roller bearing model 29480E.MB manufactured by FAG Bearing Corporation. The rear lip seal of the housing is a National Oil Seal part number 417608AS204. The thrust bearing and housing are designed to carry the entire thrust load of the pump. The bearing also shares the radial load with the lower roller assembly. The lower roller assembly does not support any of the thrust load.

The oil lip seal is designed to seal against the shaft. The lip seal is comprised of a rubber seal with an internal diameter slightly less than the shaft it is to seal against. A steel garter spring is used inside the rubber seal to increase the pressure exerted by the rubber and increase the contact of the rubber with the sealing surface. The rubber and garter spring are housed in a steel shell. The seal is housed in a circular ring that is anchored to the input shaft of the thrust bearing and has a press fit into the ring that is attached to the shaft with set screws. The sealing surface rides on a lip of the cover to the thrust bearing. The lip is a ring welded to the cover with the outside diameter surface machined to allow for the seal contact.

The bearing outer race is mounted in the housing with an interference fit. The inner race was designed to fit on the shaft with a 0.007-inch interference. The shaft interference is accomplished by inserting a tapered sleeve between the inner race and the shaft. Pressing the tapered sleeve further on to the shaft increases the interference. The sleeve has a 2° taper, and produces the 0.007-inch interference when the sleeve is pushed on 0.050 inch. The installation of the sleeve was performed in the manufacturer's shop using a hydraulic nut to apply the required force on the sleeve to move it the 0.050 inch. A left-hand-threaded locknut is installed on the shaft after setting the preload on the tapered sleeve. The purpose of the locknut is to eliminate the chance of the sleeve working loose under vibration and operating forces. The left-handed threads will tend to tighten when the pump is operating. Once the nut is tightened, a set screw is installed between the nut and shaft in the threads to eliminate the chance of the nut loosening. The thrust bearing is mounted on the same base plate as the gear box and motor, eliminating the possibility of differential movement between the equipment. Lubrication for the bearing was with an oil grade comparable to ISO 220 with an EP additive. Contract specifications required the use of food-grade lubricants. The oil was initially drained out of the thrust bearing of pump 2. The oil had a clean appearance with no noticeable contamination. The seal and seal ring were removed along with the cover. The interior of the housing had small metal turnings around the bearing and race. Samples of the turnings were collected by the manufacturer and sent in for analysis to determine their origin. The tests concluded that the turnings were the same material as the case. After further investigation, it appeared that the turnings had been in the bottom of the cover hold-down bolt holes. The debris was not cleaned out of the holes before assembly, and when the bolts were removed the turnings were pulled out with the end of the bolts. The case was cleaned thoroughly by flushing debris out of the case, refilling it with the proper lubricant, and putting it back into service. The set screw was replaced with a larger dowel pin. A 3/4-inch-diameter, 2-inch-long dowel pin replaced the original set screw (the original screw was 3/8-inch diameter and 1/2-inch long). The bearing was thoroughly cleaned of all foreign material by sweeping the interior surfaces with a magnet, using suction to remove nonferrous material, and flushing the bearing with lubricant to remove contamination from the bearing surfaces. The cover and seal were installed after cleaning, and the bearing filled with lubricant. The lubricant used was an ISO 320 at the recommendation of the FAG Bearing representative. The higher viscosity of the ISO 320 allows for a greater film thickness between the rollers and races. Because metal shavings were found in the oil, small dimples may have formed on the bearing races. While the dimples themselves are not a problem, the dimples cause raised surfaces next to them and the original lubricant would not provide the film thickness to prevent contact between the raised surface and the roller. The local climate can accommodate the increased oil viscosity.

Due to the discovery of the metal shavings in the pump 2 thrust bearing housing, pump 1 was checked to determine if there were metal shavings in the housing. The oil was drained from Pump 1. Inspection of the oil showed a large amount of small metal flakes in the oil. Analysis of the oil was inconclusive as to the source of the metal flakes, but there were elevated levels of copper and iron as well as large particles detected in the oil. The FAG Bearing representative was contacted and the analysis of the oil discussed. The level of large particles obtained from the sample was of great concern to the bearing manufacturer, but the level of copper and iron were not greater than might be expected during initial running of the pump. Upon removal of the lip seal, visual observations indicated that the seal had suffered severe damage at some time. The steel shell was partially crushed, the rubber torn in many areas, and the garter spring was broken with portions missing. Damage also included a portion of the steel shell that had the appearance of a pry mark on it, figure 17. The lip on the cover that the seal rides on was grooved from seal wear and required machining. The missing portion of the spring and part of the rubber were in the bottom of the housing laying next to the roller bearing. The only way to inspect the internal surfaces of the bearing itself was to disassemble the bearing from the housing. There also had been deformation of the set screw on the locknut. The barrel and thrust bearing assembly of pump 1 were removed from the bay, figure 18. The thrust bearing assembly was shipped to Allied Engineering in Alameda, California for disassembly and inspection. Inspection of the bearing showed a small piece of the broken spring in between

Figure 17. Damaged seal ring from thrust bearing. *Damaged seal ring, note broken spring and pry marks on steel shell.*

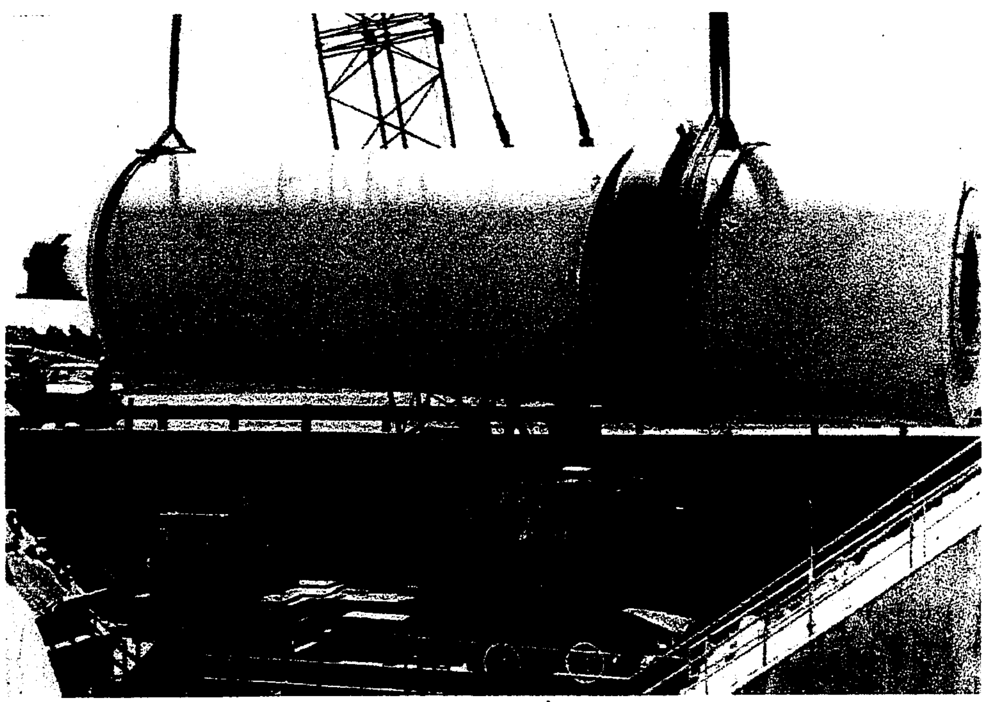


Figure 18. Removal of Pump 1 from bay. *Removal of pump 1 by mobile crane in order to repair thrust bearing.*

the rollers and outer race which could have scarred the bearing in a manner consistent with impressions on the rollers and outer race.

The damage to the outer race of the bearing on Pump 1 made the bearing unserviceable in its present condition. A new bearing from FAG Bearing was ordered and installed in the housing by Allied Engineering. The locknut was reassembled using a fabricated wrench to torque the locknut to the required 24,000 ft-lbs. The seal lip on the cover was machined to provide a good sealing surface for the oil lip seal. Larger dowel pins were added and the thrust bearing pump was cleaned and reassembled. The pry marks on the seal indicated probable damage to the seal on pump 1 when the pump arrived on site. The pry marks were located in an area that was not accessible during the erection and corresponded to the location of the garter spring break. The broken spring had entered the interior of the thrust bearing and was caught in the rollers causing irreparable damage to the races and rollers.

Saddle plates and self-aligning roller bearings. During the removal of pump 1 it was discovered that the welds between the saddle plate and pump barrel on saddle plates 15 and 16 were cracked, figure 19. The connection between the pump barrel and the power wear ring consists of 18 saddle plates welded to the exterior of the barrel with spacer blocks that are bolted to the saddle plates and pinned and bolted to the power wear ring. The power wear ring is a forged steel ring 5-inches thick and 19-inches wide. The inside radius of the ring is 3 inches larger than the external radius of the pump barrel. The crack on saddle plate 15 extended around the entire plate, and on 16, one end was cracked. Measurements of the welds showed that the weld on saddle block 15 was a 1/4-in fillet, and on saddle block 16 the weld was 3/8-in. Inspection of the remaining saddle block welds showed that all were undersized. It was apparent that during the manufacturing of the pumps, the welds were not correctly sized to allow insertion of alignment shims between the saddle plates and pump barrel at erection.

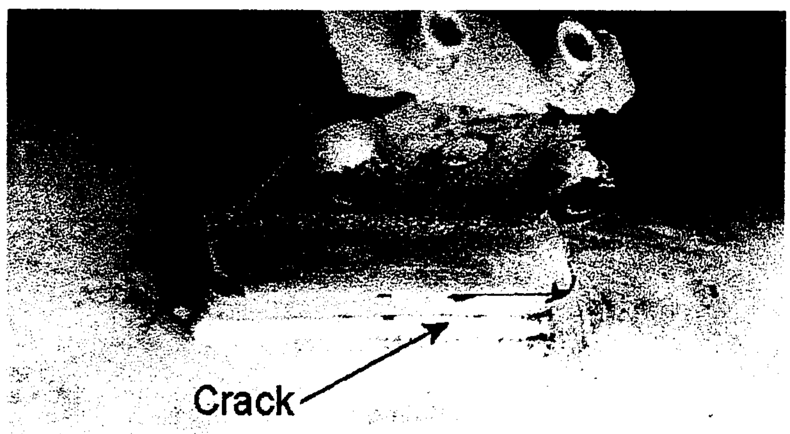


Figure 19. Saddle blocks on Pump 1. *Saddle blocks used to attach wearing ring at lower bearing location. Note crack along perimeter of weld.*

Both Archimedes pumps exhibited the same problems; and although pump 2 did not have the cracking associated with the undersized welds, the size of the welds were consistent with those on Pump 1. The welds were sand blasted to remove the paint and a magnetic particle inspection was performed to determine the extent of the welding defects. Lack of fusion, incomplete penetration, and cracking were found in the fillet welds. The repair was achieved with the roller ring in place and on-site. CPC hired a consultant, Welding Instruction Inspection and Consulting Services, Inc. (WIICS) to oversee the repair. WIICS performed magnetic-particle inspection and dye-penetrant tests on the repaired welds before final acceptance. The repairs were completed and accepted by WIICS and CPC.

During removal of the shroud for inspection and repair of the saddle plates, it was discovered that the lower bearing seal on one of the rollers of pump 2 was leaking grease. The lower roller assemblies are designed to carry the load of the pump filled with water. There are four rollers on two carriages, each carriage has two rollers. The roller assemblies consist of a shaft, two tapered bearings, seals at each end, and the cylindrical roller 16-in-diameter and 19-in-long. Each carriage is set on a steel ball to allow for movement of the carriages, providing self-alignment of the rollers to the power wear ring (mounted on the pump cylinder). The two carriages are then mounted on a common base plate bolted to the concrete and after alignment of the pump, the base plate is grouted in place. The roller shafts have a thrust shoulder that mates with a recessed machined land surface in the carriage. When the shoulder of the shaft is against the machined surface, the upper faces of the rollers will be in the same plane as the face of the power wear ring. Once the position of the rollers has been established, the anchor bolts are tightened and the base plate is grouted in place. The internal bearings of the rollers are lubricated by pressure greasing. Each shaft has a grease fitting on the center line of the axis of the shaft on the low end and a purge valve on the centerline of the axis of the shaft on the upper end. Grease is pumped in the lower end of the shaft until it exits the upper end. The quantity of grease to fully purge each roller assembly is approximately 16 lbs. The external surfaces of the rollers are lubricated with a drip oil system that is able to maintain the proper amount of lubrication between the rollers and the power wear ring. The external oiling system and the internal greased bearings are separate systems.

Pump 2 was raised and the roller removed for seal replacement and inspection of the internal bearings. The defective lower seal was inspected and replaced. The upper seal was also replaced. Inspection of the bearing revealed the grease in the bearing cap on the upper end of the bearing was extremely dry. Grease was pumped into the bearings to verify that the assembly would take grease properly without blowing the seal again. Ten 14- oz tubes of grease were added to the roller assembly before any grease was seen in the upper bearing indicating that the roller assembly had not been properly lubricated before initial start up of the pump.

The other 3 roller assemblies on pump 2 were checked for lubrication and all required substantial amounts of grease before the bearing cavities were full. A representative of CPC stated that there is to be only one purge valve on the upper side of each roller assembly. Each assembly had a purge valve on the shaft and on the upper bearing cap. The purge valve on the bearing cap on each assembly was removed and the hole plugged. The pre-load on bearings had not been set properly, and they were loose. The locknut was reset to provide the proper load on the bearing.

The roller bearings on pump 1 were also inspected as they had been submerged due to a flood at the plant. The rollers had been purged with grease after the flooding; however, Reclamation decided to replace the lower roller internal bearings at a convenient time. Upon removal of the shroud, it was noticed that the faces of the rollers were 1/4- to ½ inch offset from the face of the wear ring. The shoulders of the shafts were not against the lower side of the carriages. Closer inspection revealed that the carriages were in backwards. The recessed machined land for the shoulder was on the upper side of the carriages. The oiler was installed on the leading roller to provide lubrication on the first roller and continue to the succeeding rollers. The location of the oiler made it impossible to reinstall the carriage so that the oiler would be on the leading edge and the machined land on the lower side of the carriage. The rollers had the shoulder on the low side as required. The roller assemblies were removed and sent to Allied Engineering for replacement of the internal roller bearings. Disassembly of the roller assemblies revealed that the internal roller bearings had indications of rust on the surfaces and as a result would have had shortened the bearing life. Minor rust was observed on the roller exterior surfaces and Allied was directed by Reclamation to make a cleanup pass on the roller surfaces to recondition them. The surfaces were ground to a finish of 20 microns.

The rollers from pump 1 were completely reconditioned with replacement of the bearings, new seals and a clean up pass on the exterior bearing surface. The rollers and shafts were reassembled and installed into the carriages taking care to install the shafts with the thrust shoulders contacting the machined land in the carriage. The carriages were installed with the machined land on the lower side. The bracket for the external oiling equipment discharge was reinstalled on the opposite end of the carriage. The roller assemblies were purged according to the directions supplied by CPC representatives. Grease was pumped into the fitting on the lower end of the shaft until grease exited the purge valve.

Cracking of Internal Flights. In July 1996, cracks were discovered on the internal flights, forming at the heat-affected zones of the flight-to-flight segment butt welds. The cracks were propagating perpendicular to the welded segments, radially into the parent metal. The cracks varied in length throughout the pump, and some of the larger cracks were long enough to allow the plates to offset. The pump manufacturer (CPC) was contacted and the problem explained to them. They offered no immediate recommendation but showed concern that operating the pumps at river elevations greater than the design maximum elevation (240.5 ft) could cause excessive loading on the flights. Pump 1 had 1023.55 hours of operation when eleven cracks ranging from 1/4- to 5-1/8-inches long were discovered, figure 20. The cracks in Pump 1 extended into the flight plates in a direction perpendicular to the plate edge. The crack propagation was in a curved direction extending away from the plate-to-plate weld, figure 21. Several of the plates were offset across the crack by as much as 3/16 inch and the crack was opened by 1/8 inch. Pump 2 was also inspected and the same pattern of cracking was found. Pump 2 had 417 hours of operation and eight cracks between 1- to 4-inches long were found.

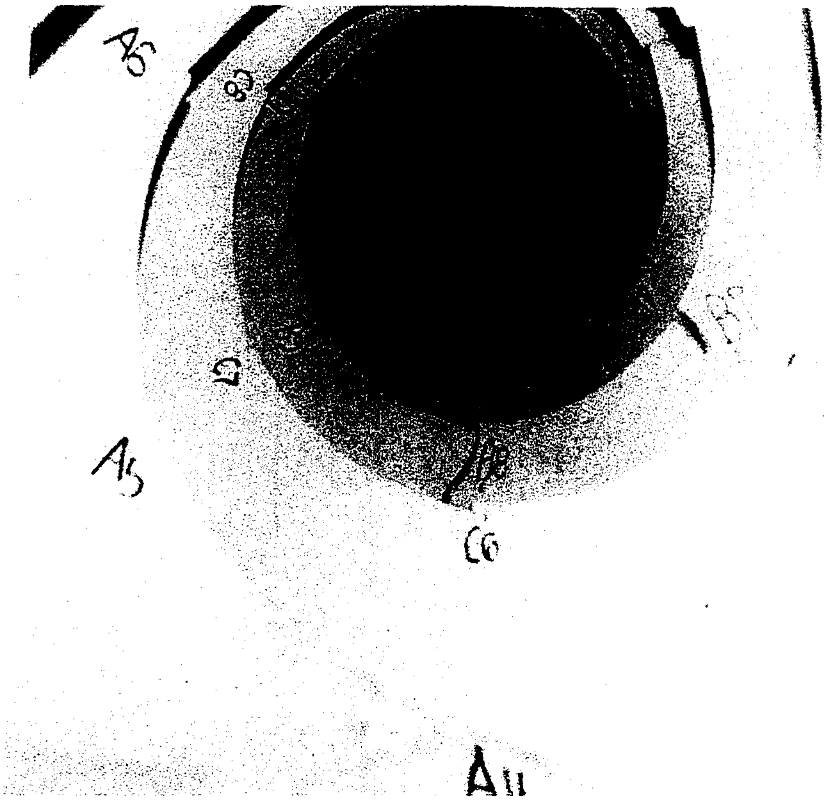


Figure 20. Cracks on the flights of Archimedes Pump 1. *View looking up the barrel of Pump 1, cracking of the flights, note that crack visibility was enhanced by rust.*

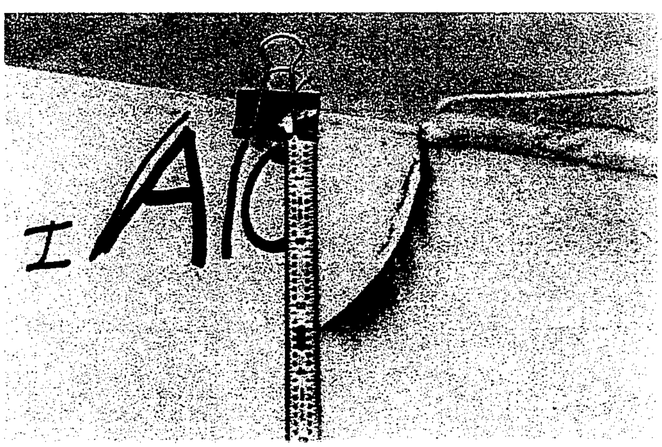


Figure 21. Typical fatigue crack propagation. *Cracking generally propagated perpendicularly from the edge of the weld. Note the abrupt material transition at the weld, responsible for stress concentration.*

The pump barrel has three major components; the outer barrel, the flights, and the shaft. The outer barrel houses the flights and the inlet end has a plate with an inlet hole to accommodate the roller pipe. The outer edge of the flights are welded to the barrel with fillet welds on the inlet side of the flights, the last 720° of each flight is welded with fillet welds on both sides of the flight. The barrel was fabricated with 10-ft sections of rolled cylindrical pipe welded together. Each 10-ft section of pipe was fabricated as two half shells welded with a longitudinal seam. The flights were formed with a series of triangular plates welded together forming a spiral inside the barrel. After the plates were cut to proper size, the triangular plates were put in a break and using a progression of small bends the plates were formed to the proper curvature. Each plate comprises a 60° rotation of the spiral, one complete rotation is 6 plates. The plates are welded together with butt welds on each side of the flight. It is not a full penetration weld. There are 5 complete rotations of each spiral for a total of 1800°. In the first 3 rotations (1080°), the plates are 1/4-in-thick, in the last 2 rotations (720°) the plates are 3/8-in-thick. The inside of the last 2 rotations are welded to the drive shaft with fillet welds. The drive shaft extends into the pump to a distance equal to the length of the last 2 rotations of the flights.

The cracks started at the interface of the triangular plates at the end of the butt weld. Using visual inspection, the first crack in pump1 was found 8 ft-11inches from the inlet, with the last crack 19 ft-11inches from the inlet. There was a total of eleven cracks. The centerline of the roller ring is 12 ft from the inlet. The cracks found in pump 2 were in the same areas. The poor contour and workmanship of the welds at the interface provided a stress riser which led to the fatigue damage.

The ends of all the plate-to-plate welds were sandblasted to allow visual and magnetic particle inspection. The existing cracks were sandblasted along their entire length plus a minimum of 2 inches beyond the known crack end. The cracks were identified with magnetic particle inspection to determine the full length. Each crack was ground out and rewelded with a full penetration weld; the welding procedure used was written by CPC, figure 22. The repaired weld was then radiographed to verify that the crack was completely removed and the repair was sound. Each of the joints between the flight plates was contoured to provide a smooth transition across the joint and to remove the existing stress risers. A minimum 1/16-inch radius was added to the edge of the plate at the joint.

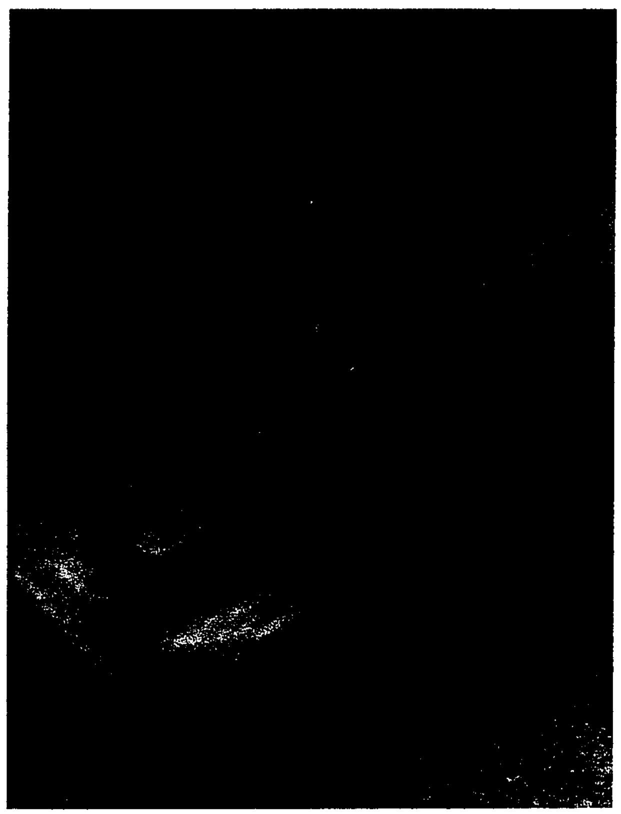


Figure 22. Weld repair to Archimedes flights. *Weld repair on cracked flight. Note contoured joint at plate interface.*

After the initial discovery of the cracking, inspections on the Archimedes pumps have been performed after approximately every 1000 hours of operation. The second inspection, performed on October 26, 1996, showed that the repairs on all components excluding the internal flights were still in acceptable condition. The alignment of the pumps were checked using a local laser alignment contractor while Bureau of Reclamation employees inspected the couplings, saddle plates, rollers, wear ring, inlet seal and flights. Oil samples were also taken from the thrust bearings, gearboxes, and lower roller oiling system. All samples indicated normal wear. The internal flights; however, had additional cracking. Pump 1, which had an additional 909.25 hours of operation,

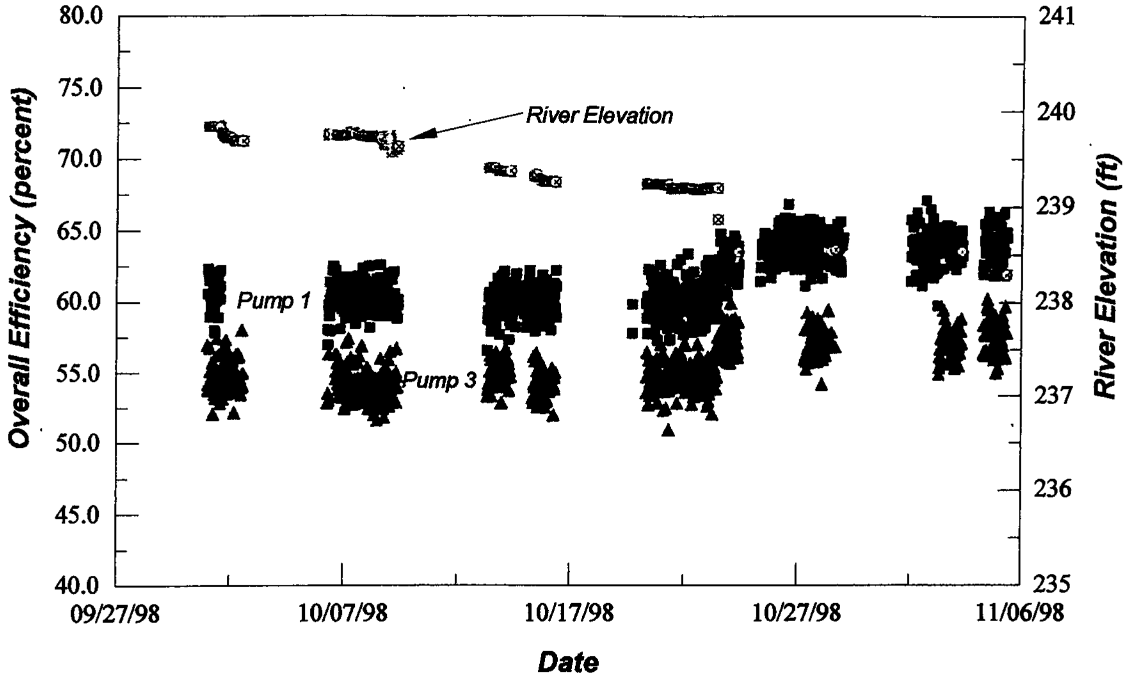


Figure 28. Overall efficiencies for 1998. *Overall efficiencies for Pumps 1 and 3 at the Red Bluff Research Pumping Plant for the last quarter of 1998.*

Screening Structure

The fish-friendly pumps deliver a mixture of water, fish, and debris which then needs to be separated by some method. The method used at Red Bluff is to screen the flow after pumping and concentrate the fish into a much smaller (10-percent) volume of flow. The concentrated fish, water, and debris then pass through a bypass channel to evaluation facilities or back into the river. Basic guidelines exist for the design of screening and bypass facilities [Rainey 1985].

Each of the pumps at RBRPP terminates in a free fall into a channel of water. This channel carries water, fish, and debris to the screening facility. After a short length of channel, a chevron or vee-screen structure concentrates the entrained fish into about 10-percent of the total pumped flow which then passes down a bypass into the fish evaluation facility. The screen structure features twelve 5.25-ft by 5.25-ft panels of stainless steel No. 69 wedgewire screen. The wedgewire has a vertical orientation and features 5/32-inch bars with 3/32-inch openings. The vee's are at a half angle of 4.89-degrees, figure 29. Original plans did not include baffles. The screens are equipped with continuously operating brushes to clean the panels. Water levels in the channels are adjustable using weir gates on the canal return flows and using a motorized gate in the fish evaluation facility.

The pumps discharge into an enlarged rectangular channel section. The Archimedes pumps dump the contents of each flight into the head end of the channel at a rate of 79.5 cycles/min when the pumps operate at full speed. A discharge of 90 ft^3/s requires that about 68 ft^3 of water be carried in each flight segment at the maximum speed of the pumps. The first 17 ft of the channel in which the Archimedes pumps dump into is covered by the concrete mounting block that supports the pump motors and couplings, figure 30. The initial 7 ft of the channel is a modified trapezoidal shape which transitions into a rectangular channel over the next 14.25 ft. The vertical fish screens begin 1 ft into the rectangular section. The Wemco-Hidrostal centrifugal-helical pump discharges at a similar position in the channel although the outlet is offset and not centered on the channel, figure 31. The off-center discharge impacts on the transitional fillet at the bottom of the channel causing a back and forth sloshing to occur for a considerable distance down the channel.

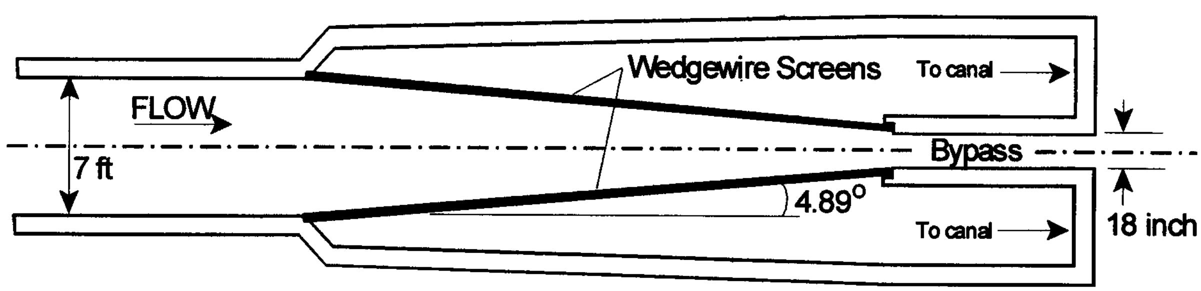


Figure 29. Partial plan of one screen bay. *Partial plan of one screen bay, showing location and angle of the wedgewire screen panels.*

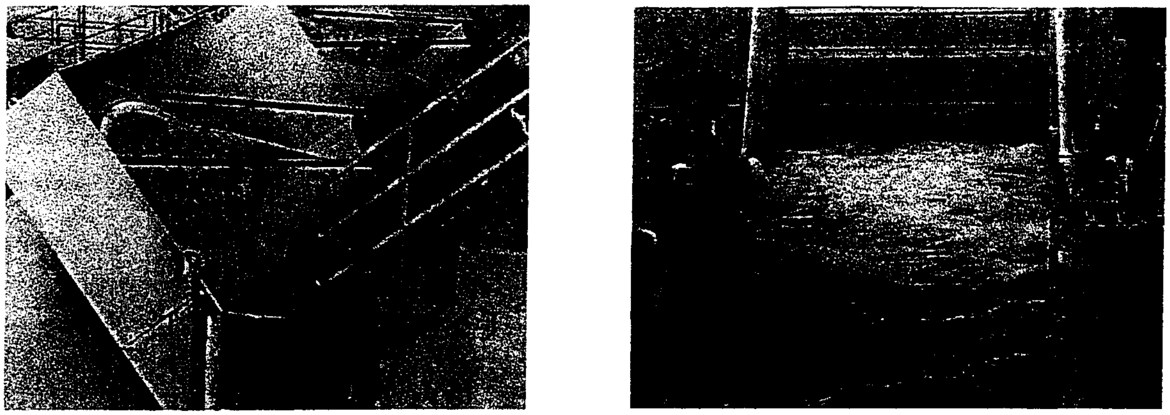


Figure 30. Archimedes pump discharge. *Discharge area for the Archimedes pumps. Left photo shows the end of the pumps while the right photo shows the discharge channel after about 17 ft of channel length.*

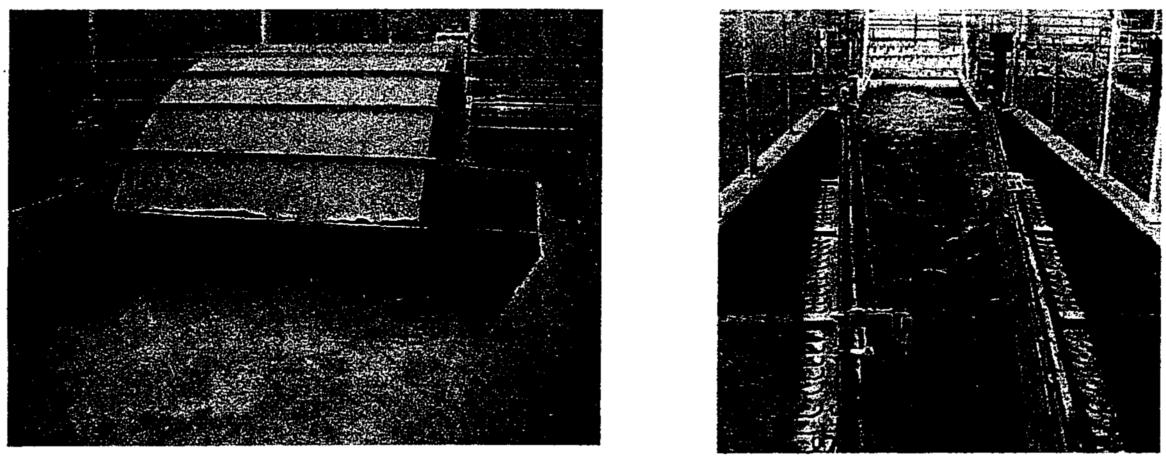


Figure 31. WEMCO-Hidrostal pump discharge. *Wemco centrifugal-helical pump discharging about 80 ft^3/s into screening channel. Left photo shows offset discharge to channel. Right photo shows channel and a portion of the vee screen structure.*

The main operational requirements of the fish screening structures are to meet screen criteria set forth by the resource agencies (California Department of Fish and Game and National Marine Fisheries Service). At the time of the original design and construction, the approach velocity to the screens was dictated by the California Fish and Game criteria of 0.33 ft/s at a point about 3-inches off the screen face, figure 32. However, since that time, a criteria modification was published by the National Marine Fisheries Service [1997], and was accepted by California Fish and Game, becoming effective in February 1997. This new criteria states that for fry-sized salmonids the approach velocity should not exceed 0.4 ft/s for canals (off river). This criteria also references measurements about 3 inches off the screen face. In addition to meeting screening criteria, the structure must also

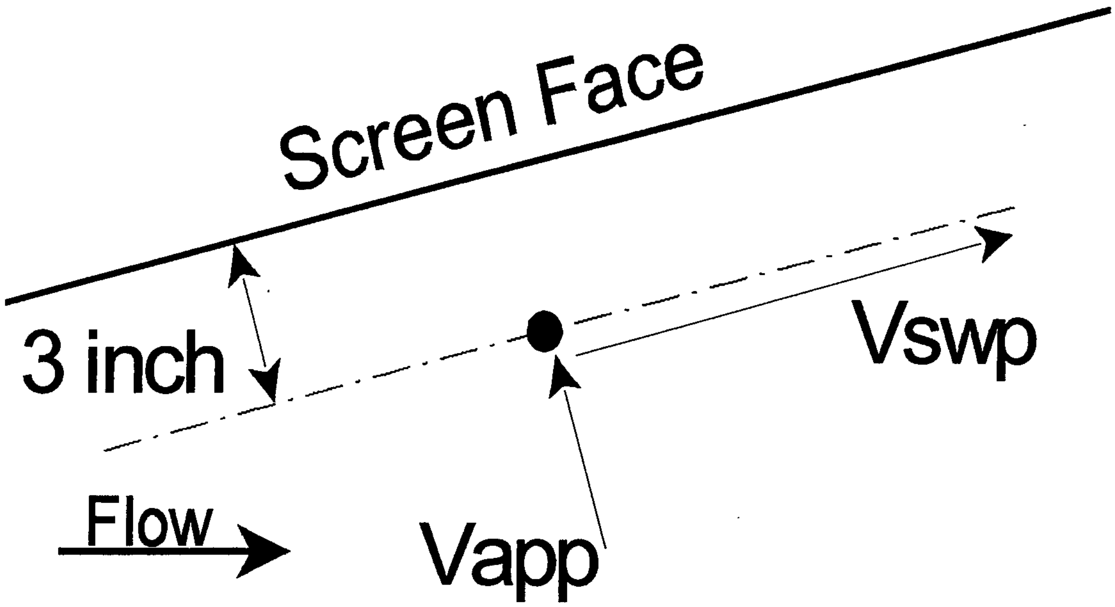


Figure 32. Velocity component definitions. *Approach and sweeping velocity components at a point 3 inches off the screen face.*

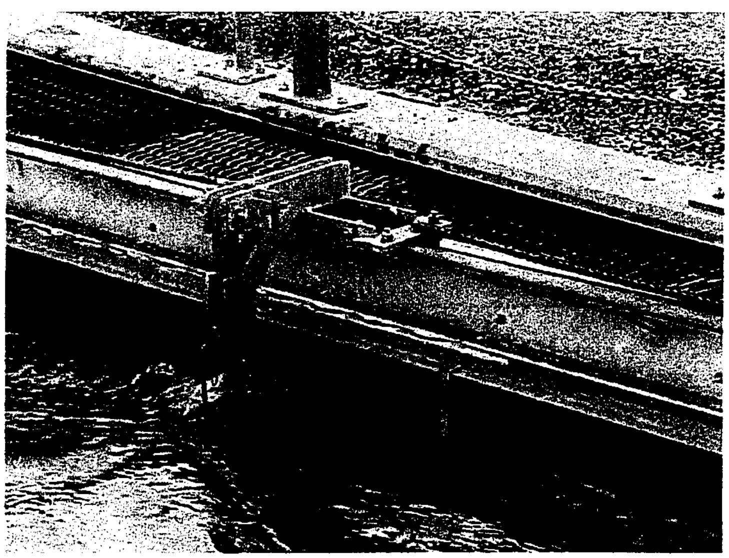


Figure 33. Sweeper in action. *Continuous operating sweepers run back and forth over the wedgewire screen, brush extends the full depth of the channel.*

be able to handle debris without plugging the screens. Continuously operated brushes sweep each side of the structure using a spring-loaded full length brush, figure 33.

After some cursory point velocity measurements, it was clearly apparent that some type of baffling of the screens at RBRPP would be necessary to reduce approach velocities and to distribute them more evenly over the entire screen surface. Initial measurements were performed in June 1995 on the internal-helical pump channel with no baffles installed. Approach velocities in excess of 1.25 ft/s were measured behind the screen panels using an OTT propeller current meter. Prior experience with similar screening structures in the field and laboratory models [Mefford and Kubitschek 1997, Vermeyen 1996] have shown that in order to effect the velocity magnitudes and distributions, baffles with open areas of 25-percent or less were required. Some field observations at other sites have shown that adjustable baffles near the bypass entrances had to be almost entirely closed. Initial measurements were performed on the screen structure of pump 3.

The first attempt at baffling was with fixed area baffles constructed of plywood and bolted to the backside of the downstream half of each side of the structure, figure 34. These were installed in July 1995. The screen panels closest to the bypass entrance were baffled with 10% open area, the next ones upstream at 25%, and the final baffles were at 50% open area. The upstream 3 panels on each side of the screen structure remained unbaffled. The baffling as a function of the complete screen area was 64 % open.

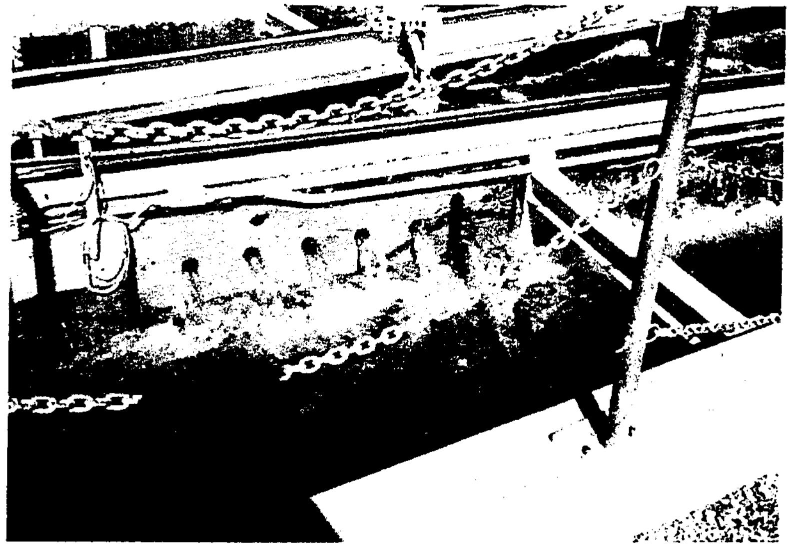


Figure 34. Temporary plywood baffles. *Plywood sheets with holes cut out created temporary baffles behind the wedgewire screens.*

Velocity measurements were made with a 3-component ADV (acoustic doppler velocimeter) manufactured by SONTEK, figure 35. This instrument measures the three components of velocity in a small volume of water 2 inches below the sensor head. Measurements were made at a rate of 25 Hz, with average velocities based on 1500 samples at each point. Vertical profiles were collected at a point 3 inches off the screen face. Some improvement in the velocity distribution was accomplished but the magnitudes were still not entirely within criteria. Maximum approach velocities were 0.6 ft/s, with sweeping velocities averaging between 2 and 3 ft/s. In addition, a large recirculation zone was discovered near the bypass entrance. This eddy-zone was caused by the 4:1 ramp located in the bypass channel, beginning about 2 ft downstream from the start of the 18-inch-wide bypass channel. The baffles had little affect on the large eddy. Deposition of sediments (small gravel) within the screen structure coincided with the upstream extent of the eddy zone.

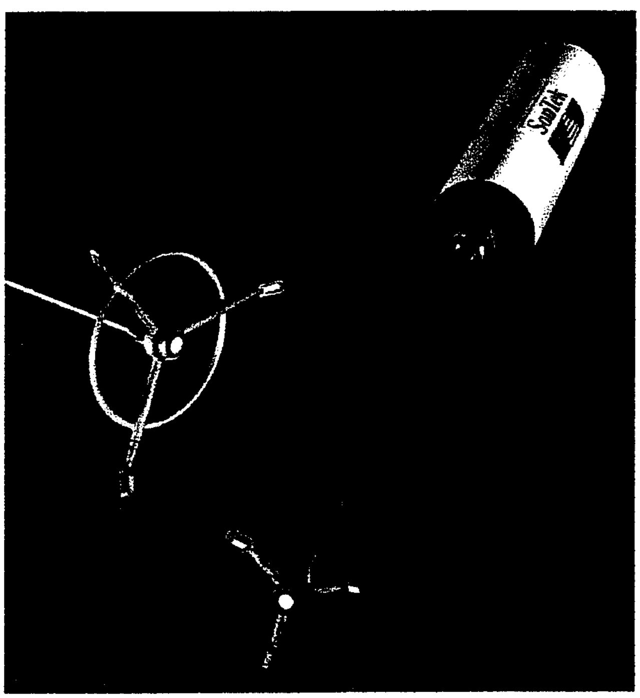


Figure 35. Sontek ADV probe. *Photograph of 3D Sontek ADV probe, insert shows detail of probe head.*

The early fish injection experiments also pointed out the problem with the velocity field entering the bypass, as many fish would hang up in front of the bypass entrance in the eddy zone created by the bypass ramp. Adjustable porosity baffles were constructed and replaced the *partial* temporary baffles in September

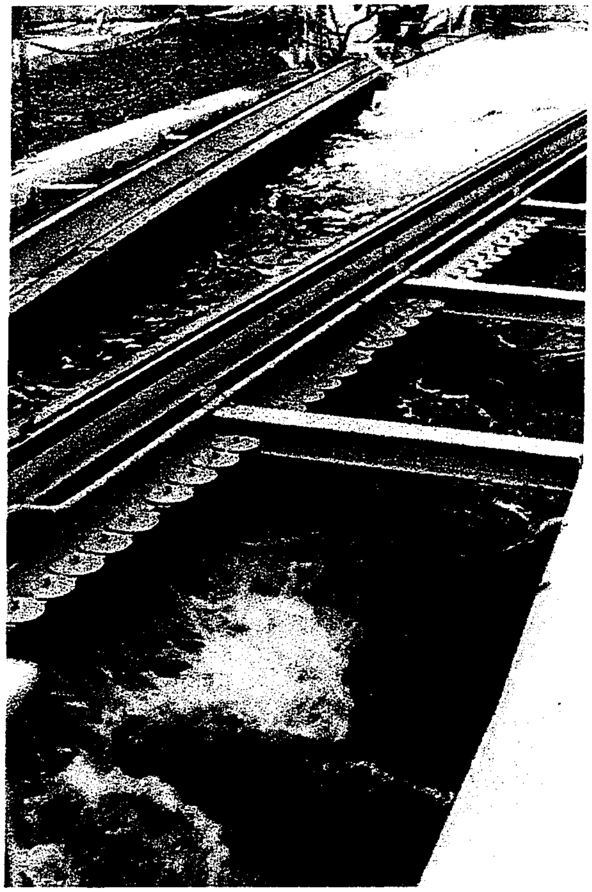


Figure 36. Adjustable baffles. *Adjustable porosity baffles cover the downstream half of the screen area in each bay.*

1996, figure 36. Several iterations of baffle adjustments were made between the baffle installation and summer 1997, with a complete set of measurements on all three pumps completed in July 1997. Some improvement in the velocity distribution and magnitude of approach velocities was accomplished, however, as baffles were closed off, the higher magnitude velocities migrated upstream to the first screen panel which was not baffled. Modification of the velocity distribution also helped lessen the strength of the eddy in front of the bypass entrance. Depending on the time of year and the debris load entering the screen structures, a moderate improvement in overall uniformity was achieved due to the "self-baffling" of the screens with debris. Deciduous tree leaves were especially effective in covering areas of high approach velocity on the wedgewire screens.. In addition to the baffle modifications, an adjustable inverted weir was installed shortly after the adjustable baffles, at the bypass entrance. This weir had only a very localized effect on the bypass velocity and is generally recommended that it not be used, however, it does help maintain the water surface within the screen structure.

Detailed velocity measurements of the flow field in front of the wedgewire screens with the adjustable baffles in place were performed once again in the summer of 1998. Measurements were performed on pump 2, an Archimedes pump operating at 26.5 rev/m. Results show that the approach velocities near the bypass entrance were within criteria, however, just upstream from the beginning of the baffles, high approach velocities still exist, figure 37. The uniformity of the velocity field was also slightly variable, especially side to side. It became clear that it was necessary to baffle all the screen panels to affect the entire velocity field. Plywood baffles with a 25-percent open area were installed behind the remaining unbaffled screen panels. The measurements were repeated and showed much improvement in both magnitude and uniformity, figure 38. In general, the approach velocities met the 0.4 ft/s criteria at almost all points measured. The area in which criteria is exceeded is most likely due to the influence of surface waves impacting the wedgewire screen. The waves are noticeable in the Archimedes pump

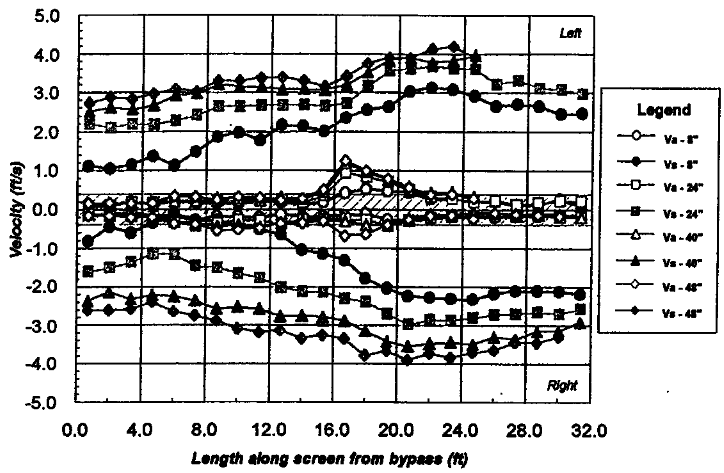


Figure 37. Velocity measurements for partially baffled screens. *ADV measurements for partially baffled screens of pump 2, $Q=87\ ft^3/s$. Measurements are for various depths above the channel bottom.*

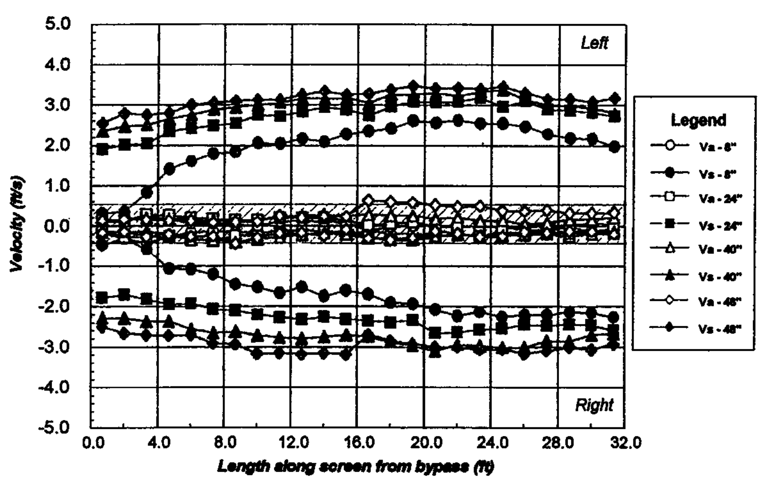


Figure 38. Velocity measurements for fully baffled screens. *ADV measurements for fully baffled screens of pump 2, $Q=87\ ft^3/s$. Measurements are for various depths above the channel bottom.*

channels and the frequency is a function pump speed. At maximum speed (26.5 r/min) the dumping frequency of the flights is 1.325 Hz, and while not noticeable in the actual velocity traces, the water surface is definitely not smooth As the rotational speed of the pump is slowed down using the variable frequency drive, the waves or pulsing action of the flow does become noticeable in the actual approach and sweeping velocity measurements, figure 39.

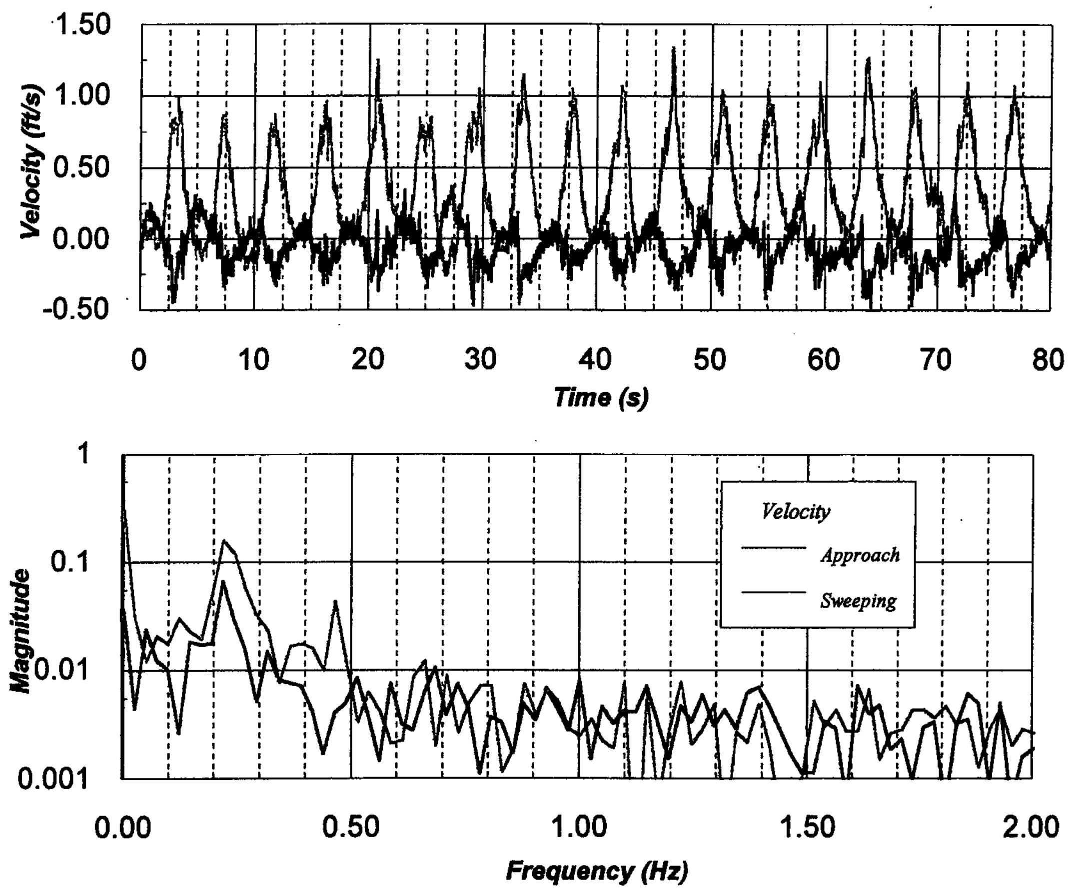


Figure 39. Velocity measurements with the Archimedes pump rotating at 4.42 r/min. *Time series and frequency information of the approach and sweeping velocity components from pump No. 2, operating with the VFD at 10 Hz, giving a rotational speed of 4.4167 r/min and a dumping frequency of 0.22 Hz, Q=12 ft³/s.*

In addition to the screen velocity measurements, mean channel velocity profiles were measured using a Marsh McBirney electomagnetic current meter on pump 2. Three cross-sections through the screen structure were measured, one 3 feet upstream from the beginning of the wedgewire screens, one midway through the vee-screen structure, and one at the bypass entrance. These cross-sections were also measured for both partially and fully baffled conditions. Although not a dramatic difference, the fully baffled measurements did show a slightly more uniform channel velocity distribution upstream from the beginning of the vee-screens, figure 40. Measurements at the midpoint of the vee-screens and the entrance to the bypass channel showed a deceleration in the mean downstream channel velocity. Whereas the average velocity in the channel upstream from the screens is about 3 ft/s, the velocities entering the bypass are down to around 2 ft/s. Although the recirculation eddy near the floor is less pronounced, flow still does not accelerate through the structure and into the bypass. While the uniformity of the approach velocities are improved with the fully baffled conditions, the downstream channel velocity still shows non-uniform distributions with higher velocities on the left side of the structure (looking downstream).

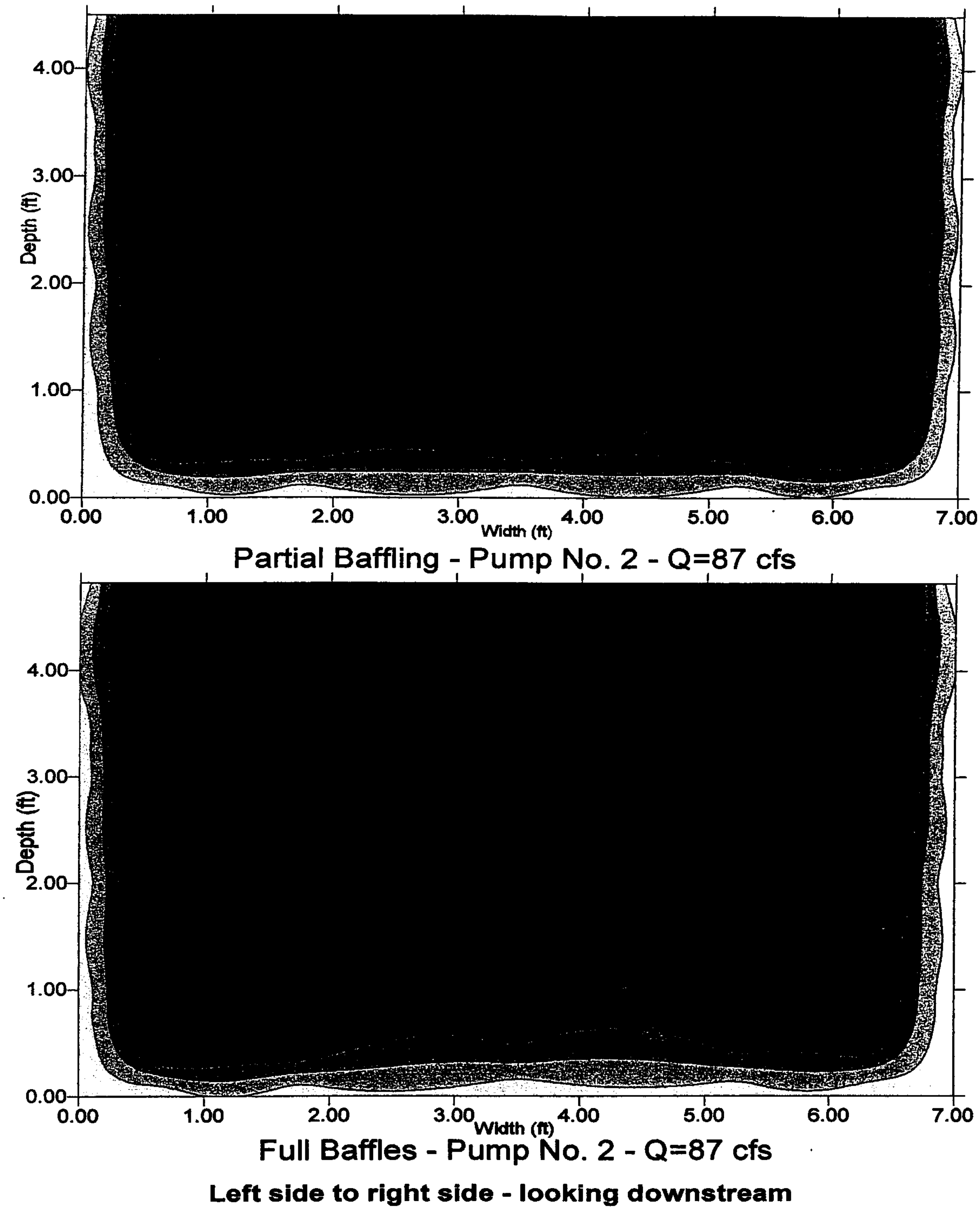


Figure 40. Cross-section velocity maps, 3 ft upstream from the beginning of the vee-screens. *Isovels from measurements with a Marsh McBirney electromagnetic current meter, 3 ft upstream from the beginning of the vee-screen structure on pump 2.*

Fish Evaluation Facility, Bypass, and Canal Discharge

Evaluation of fish condition after passing through the many features of the pumping plant is a very important aspect of the research program. Approximately 10-percent of the total pumped flow from each pump along with fish and debris, pass down long radius sweeping channels to a series of holding tanks, figure 41. Additional dewatering, using an adjustable wedgewire ramp, further concentrates the fish before they enter the holding tanks. Each pump bypass is equipped with two holding tanks. The bypass flows continue through underground piping and intersect the existing drum screen bypass from the Tehama Colusa canal screening facility. Each of these buried lines features a magnetic flow meter to measure discharge and a pinch valve to allow the facility to be isolated from the river. The majority of the pumped flow passes to the canal through 3 buried pipelines after having been screened in the vertical screening structure. Each of these lines exits into the TCC and features a propeller-type current meter at the discharge end.

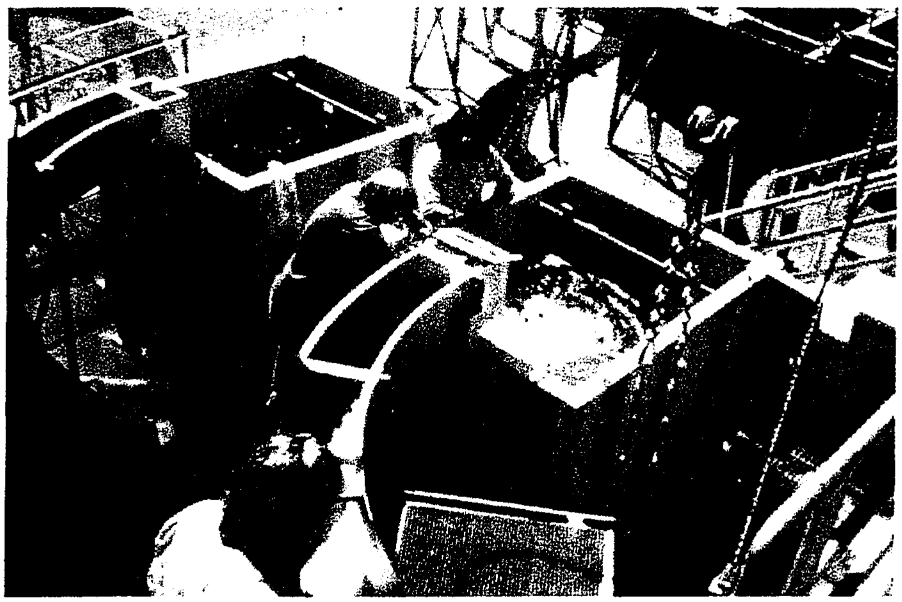


Figure 41. Holding facility. *Holding tanks are able to catch the bypass flow, allowing for collection of fish which have come through the pumps.*

The main engineering evaluation component of the bypasses and the fish evaluation facility was to insure that no structural feature impedes or injures fish entering the facility. To evaluate the direct effect of the two types of fish-friendly pumps on fish condition and survival, there needs to be confidence that other parts of the structure are not adversely influencing their condition. No specific engineering evaluations were conducted. Several changes were made to the facility, mostly involving plugging holes and gaps which were allowing fish to escape around the dewatering ramp and avoid the holding tanks. In addition, several modifications which allow for easier and more efficient operation of the holding tanks and flow adjustment were performed. Preliminary fish passage trials indicate that the screening and evaluation facilities which the fish encounter after passing through the pumps, do not increase the incidents of mortality [McNabb, et.al., 1998].

No specific engineering evaluations have been performed on the bypass lines from the evaluation facility back to the river. Currently, studies regarding the characteristics of the bypasses are being conducted by the RBRPP staff. Some maintenance has been required on the pinch valves, but the system has performed well. The return flows from the screen structures to the canal (screened water) are measured using a propeller type flowmeter mounted at the exit of the pipes into the canal, figure 42.

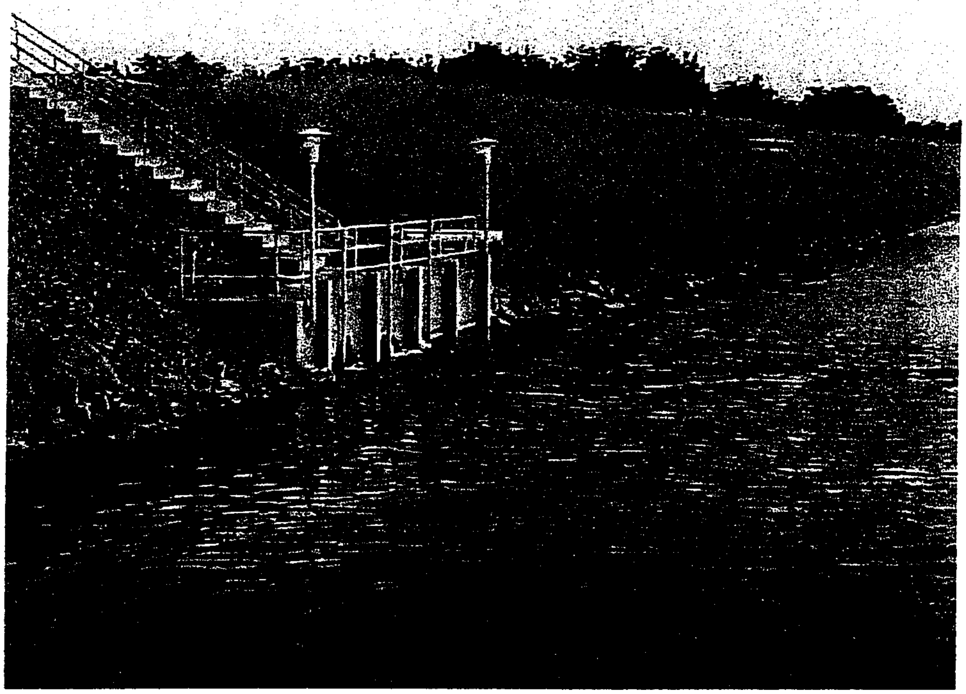


Figure 42. Terminal structure for the screened flows from RBRPP. *Water flows which are screened in the vee-screen structures flow through buried pipelines and exit into the Tehama-Colusa canal at the structure shown above. Propeller-type flowmeters measure the flow from each pipe flowing into the canal.*

Discussion

The studies which have been performed to date at the Red Bluff Research Pumping Plant have been extensive and varied, including both biological and engineering evaluations. Assessing the impact of a physical feature, such as the pumping plant, on fish populations inhabiting the Sacramento River at this location is just one of the objectives of these studies. While the driving force behind this research is related largely to biological results, the complex interaction of the engineering features with the resulting biological performance cannot be separated. In general, the design, construction and operation of a pumping plant are tasks which with experience, can be performed by many engineering organizations. However, in the past, the environmental impact of these types of facilities has mostly been an afterthought. From its inception, this project has used a multi-disciplinary approach throughout the planning, design, construction, and evaluation phases.

Since the initial startup of the pumps in 1995, the onsite engineering staff has spent the majority of their time trying to keep the plant operational so that the planned evaluations could take place and remain somewhat on schedule. This has been no easy task. The engineering evaluations which have occurred over the past 4 years have been largely in support of the biological studies and have therefore needed to remain flexible both on their objectives and schedule. The engineering evaluation plans have always remained general in terms of the overall goals and objectives.

The Sacramento River and Inlet Structure

There has been a fairly long history of study in the river of both hydrologic and hydraulic parameters. There is a long record of flows in the river from the U.S. Geological Survey, showing both pre- and post-Shasta Dam. In addition, a number of studies including sedimentation and debris, were performed during the planning or shortly after construction of the Red Bluff diversion dam. The engineering studies associated with the Red Bluff Research Pumping Plant should build on the prior database.

It is very difficult to evaluate the inlet structure as a generalized design, due to the very site-specific nature of siting a structure such as this on a river. Observations of the performance of the inlet structure can be compared to the original design goals, and changes addressed if needed. In addition, the very complex interactions of the river and plant vary from year to year depending on climatic changes as well as changes in operation at Shasta Dam.

The formal engineering evaluation in the river has consisted of ADCP measurements of bottom profiles and river velocities at a number of sections upstream and downstream from the RBDD. The measurements were taken in what are considered to be normal to wet water years, with considerably different results expected if repeated during an extended drought period. Again, generalizations are hard to make based on the complex behavior of the riverine environment at a specific site, exposed to specific conditions.

The inlet structure has caused some operational problems, mostly due to deposition of sediments in the structure itself. While the pumps have continued to operate, an equilibrium deposit of sediments is maintained in and around the inlet structure. No impact on performance has been noted. The sizes and amount of sediments within the structure varies depending on river flows, storm events, and geomorphologic changes within the adjacent river environment. Initial goals of providing strong sweeping velocities past the intake structure have been achieved, however, currents within the structure itself do not maintain the high magnitudes directly in front of the pump entrances, thus the deposition. On several occasions, partial removal of sand and gravel from the inlet structure have occurred. In December 1998 Reclamation contracted a dive team to remove all the material behind the trashracks. They used a 6-inch dredge. The upper trashrack was removed so that the muck could be discharged over the top of the lower trashrack. A system was installed to flush the bulkhead gate slots to allow seating of the bulkhead gates. One change in position of the angled trashracks has been performed. Sweeping velocities in front of the inlet structure were improved but it has been difficult to determine their effect of deposition of material behind the trashracks. The current position has all bars angled downstream, in much the same configuration as a rack of louvers. In addition, solid plates were added to the bottom 18-inches of the trashracks and has not entirely excluded sediments from the structure. The major cause of sediment deposition within the structure appears to be due to suspended sediments during large flow events, with some contribution also due to movement of bed load.

The Pumps

The major feature of both the biological and engineering evaluations are the pumps themselves. Two varieties of fish-friendly pumps were chosen due to their proven abilities to pass fish and other delicate solids without damage. Pump usage, either as the main diversion or as a screened bypass requires a survival rate of near 100-percent, especially when there are endangered and/or threatened species which may encounter the pumps. Each style of pump installed, the Internalift Archimedes pump and the Wemco-Hidrostal centrifugal-helical pump, are at the upper end in size and discharge of previously manufactured pumps of these types. The chronology of pump operations detailed in this report shows a large amount of down time for each pump. The problems which resulted in the down time can be broken into two major categories: problems due to design inadequacies, and problems due to improper or poor manufacture and installation. It is important to realize that the majority of the down time for the Archimedes pumps was due to poor manufacturing and improper installation while for the Wemco-Hidrostal, most problems were design related. This difference is somewhat understandable as the Wemco pump is the largest one ever manufactured, and almost twice as large in size and discharge to anything that has been previously designed. Archimedes pumps of this size have been built before, although they typically are designed for a different type of inlet condition as well as for slower rotational speeds.

The major design issues with the Archimedes pump involved the rotating seal at the inlet to the pump and the design of the internal flights. Most of the additional problems including failures of couplings and bearings were due to the initial installation being well out of alignment. The rotating seal provided by the pump manufacturer failed within hours of the startup. After several months of trying to work with the manufacturer, Reclamation finally designed and installed a seal which has been performing very well. There has been little or no maintenance required, and leakage was minimal. Cracking of the pump's internal flights was the other major design issue. This problem was a result of both an overload and poor workmanship of the flight-to-flight welds. The cracking began at an abrupt contour change and the beginning of a weld. This type of junction typically has a large stress concentration factor. In addition to this workmanship issue, finite element modeling showed that the size material used for the flights were inadequate. Reinforcing plates were added to each side of the flights over a portion of the pump's length. Through this modification as well as the weld repairs and stop-drilling, most of the cracking has stopped. The setting of the pump elevation in the structure may be a major cause of the cracking due to the high static water loading inside the pump. The lack of experience with a variable water surface at the inlet to the Archimedes pump raises the question as to whether a higher pump elevation setting should have been used. Figure 43 shows the minimum and maximum design water surfaces and how they relate to the pump setting.

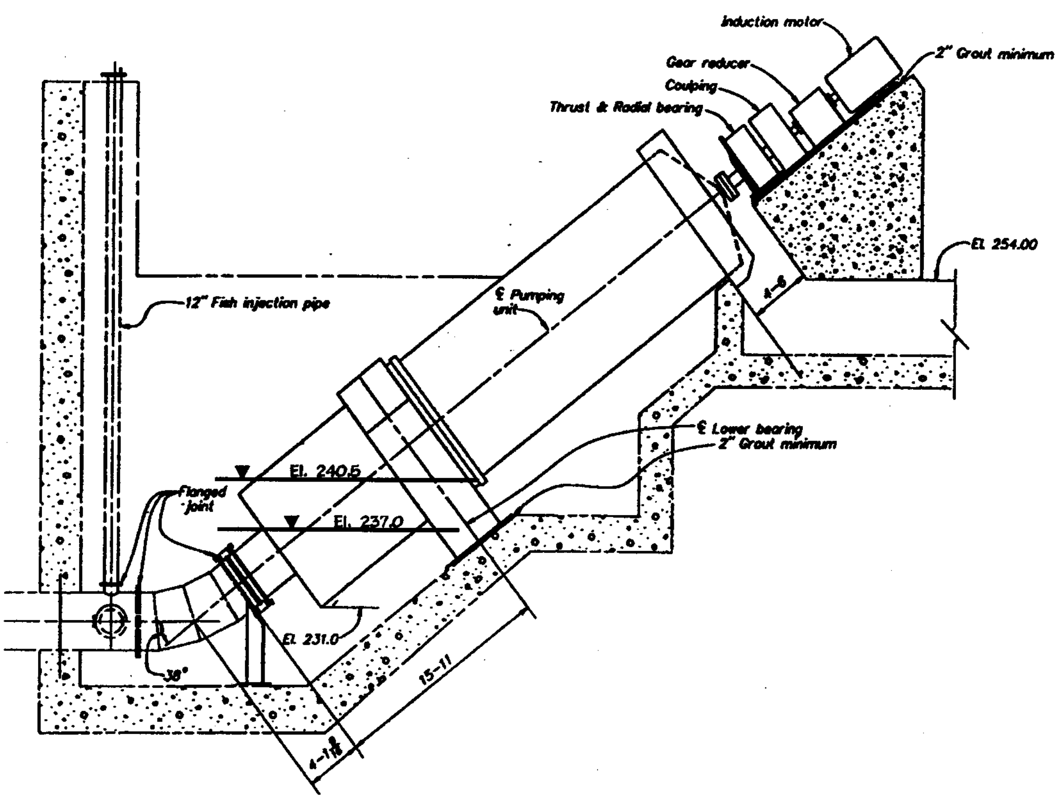


Figure 43. Elevation setting of the Internalift Archimedes pumps. *Design settings for the Archimedes pumps at RBRPP. Note specified minimum and maximum water surface elevations for pumping, actual maximum was actually closer to 245.*

Screening Structure, Bypass, and Evaluation Facility

The screening structures have perhaps the most interesting hydraulic conditions within the entire structure, mostly due to the need to meet fish screen criteria. Some initial design oversights were quickly addressed once the pumps began operating. Included in these oversights were baffles. It was realized that baffles would be needed to achieve uniform flow conditions, however, none were in the original design. Through many rounds of measurements, the screen criteria was finally met with a full set of baffles behind the wedgewire screen panels. All prior attempts using partially baffled screens of fixed or adjustable porosity were unsuccessful in meeting criteria. Several structural design features also contributed to difficulties in meeting criteria. Included in these features were: relatively short length and small volume approach channel to the vee-screens, and the bypass design caused a deceleration of flow through the screen structure, inducing a recirculating zone or eddy in the bottom 2 ft of flow depth which affects conditions within the screen structure.

For both types of pumps, the size of the channel and the outlet conditions tend to create a large amount of aeration and surface waves. The short length of channel before the screens begin (27 ft) does not allow for much energy dissipation or stilling of the flow. This in turn causes surface waves to impact the wedgewire screens making it nearly impossible to consistently achieve criteria for approach velocities, especially near the surface. Due to the size of the channels, modifications to allow comparative studies of different configurations or pump outlets have not been possible. There has been much discussion on the affect of having the Wemco-Hidrostal centrifugal-helical pump enter the channel near the bottom in a submerged jet rather than the free-falling plunge of the current configuration. Fine tuning of the hydraulic design could be accomplished in a scale model, however, its effect on fish would need to be evaluated in a prototype facility.

The channel velocity, and in particular the ratio of the sweeping velocity to the approach velocity is another design parameter where systematic testing is lacking. In the past, screen criteria's have recommended that the sweeping velocity be twice the approach velocity. The vee-screen structure at RBRPP typically has sweeping-to-approach ratios of 6 to 10 times. Some questions regarding this ratio are: can higher approach velocities be tolerated with large sweeping velocities; and are the ratios more important than the actual velocity magnitudes. There have been a number of studies involving bypass hydraulics and the most appropriate level of acceleration to guide certain species into a bypass. In addition, bypass widths greater than 1 ft are highly recommended. The specific bypass design at RBRPP will not allow an accelerating flow into the bypass at maximum flow conditions. This type of design flaw can easily be avoided, but as in the case at Red Bluff, difficult to fix in a retrofit situation. The use of ramps within bypass channels is fairly common but should be reviewed carefully to see that eddy zones or deceleration of the bypass flow is avoided.

No hydraulic evaluations have been performed on the actual bypass return to the Sacramento River. Some biological testing of the bypass system has been performed. The use of the existing drum-screen bypass lines and outfall structure have provided a less-than-optimum design for the RBRPP bypass system. The use of the existing system has been effective when run in conjunction with pulsed flows from the drum screen structure. Once again, a bypass return and outfall structure is a very site-specific and operationally-specific design. The performance of the system in use at Red Bluff should not be used to judge the state-of-the-art in bypass design.

The evaluation facility has performed well throughout the testing after a few modifications were performed to plug some pathways for escaping fish. The holding tanks have operated well except in conditions of high levels of debris. With large amounts of debris, especially if it consists of mostly deciduous leaves, around-the-clock monitoring of the facility is needed to prevent shut down due to plugging of the dewatering ramp. In terms of the fish condition, survival appears to be negatively effected by large concentrations of debris in the holding tanks. More frequent collections from the holding tanks are necessary to truly evaluate fish condition as a function of having passed through the pumping plant when the debris loads are high.

Recommendations for Future Testing

Most of the goals and objectives of the engineering evaluations at Red Bluff Research Pumping Plant have been met. A few specific measurements remain to be made, and collection of pump performance data using the automated system is ongoing. Additional documentation of the physical conditions, i.e. pressure and velocity, in the pump outfalls into the screen channels remain to be measured. In addition, documentation of both Archimedes and centrifugal pump performance at various rotational speeds remains. Final documentation of the screen performance for pumps 1 and 3 will be completed in the summer of 1999.

Acknowledgments

Many people have contributed to the engineering evaluations and operation and maintenance of the Red Bluff Research Pumping Plant. Many of the initial design concepts for the plant can be credited to Perry Johnson (retired Reclamation) and Rick Christensen (Reclamation) and the other members of the Interagency Advisory Group and Fisheries Workgroup working on the Red Bluff Fish Passage Program. Keeping the plant operational was largely accomplished by the onsite engineering staff, including Max Stodolski, Manager, and Hank Harrington (Civil Engineer with the Northern California Area Office). Reclamation's O&M staffs at Red Bluff Diversion Dam and Shasta Dam were involved in constructing and installing some of the many modifications which were installed over the course of the past 4 years. In addition, the biological evaluation team (including the many student aides) at Red Bluff, originally led by Cal McNabb and later by Sandy Borthwick, also assisted in data collection and some of the physical modifications. Special thanks go to Charles Liston (Reclamation's TSC Lead), for his guidance and support and his enthusiasm to foster a truly cooperative effort among engineers and biologists during the course of this evaluation.

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APPENDIX

Chronology of pump operations and major maintenance

5/22/1995	Pumps 1 & 2 startup testing	8 hour test - UHMW seal material present in screen channels, inspection reveals severe gouging of seal. Seal redesign needed before further operation.
5/22/1995	Pump 3 startup testing	8 hour test - no problems noticed. Pump goes into operation for evaluations.
9/14/1995	Pump 3 shut down.	Severe vibration and noise forced shutdown. Upon inspection, a broken shaft between the gear box and impeller was discovered.
3/14/1996	Pumps 1 & 2 return to service	Reclamation redesigned and replaced rotating seal.
4/25/1996	Pump 2 shut down.	Low-speed coupling failure.
5/16/1996	Pump 1 shut down.	Inspection also reveals low-speed coupling failure.
6-7/1996	Pump 1 & 2 major inspections and maintenance	Numerous problems discovered: low-speed couplings lacked grease, major alignment problems on both pumps 1 & 2, thrust bearing on pump 2 required maintenance, thrust bearing on pump 1 required replacement, self-aligning roller bearings on pumps 1 & 2 required work to correct assembly problems, saddle plates holding the wear ring to the pump cans needed weld repair for cracking, internal flights on pumps 1 & 2 exhibited cracking, all cracks were weld repaired and the plate interface was contoured,
7/23/1996	Pump 3 returned to service	Impeller had not been previously dynamically balanced. Significant weights (>100 lb) were added.
9/3/1996	Pump 3 shut down	severe imbalance noted, failure of the packing box, manufacturer recommends a new impeller.
9/14/1996	Pumps 1 & 2 return to service	Numerous repairs completed. Including installation of oil recovery system.
10/26/1996	Pumps 1 & 2 inspection	Internal flights inspected. Cracks continue to form and grow. Cracks > 3 inch were weld repaired, those shorter were stop drilled.
2/3/1997	Pump 3 returns to service	Pump 3 with new impeller begins operation.
3/10/1997	Pump 3 shut down	Rapid increase in noise and vibration force shut down, inspection reveals broken shaft.
3/26/1997	Pump 3 back in service	New shaft and wear ring installed
4/4/1997	Pump 1 & 2 inspection	Cracking still continues, both new cracks and continued propagation of stop drilled cracks.
4/19/1997	Pump 3 shut down	Vibration caused due to movement of shims under bearing housing. Pump was realigned and restarted.

5/1/1997	Pump 3 back in service	
6/4/1997	Pump 1& 2 inspection	New cracks still forming and old cracks continue to grow.
7/9/1997	Pump 3 shut down	Runout, noise, and vibration too excessive to allow further operation. Bearing housings were reworked, including reversing one set of bearings to take a thrust load. Reclamation modified the cooling-water system.
9/4/1997	Pump 3 back in service	
9/11/1997	Pump 1 & 2 return to service	reinforcement of the internal flights completed.
9/27/1997	Pump 3 shut down	Coupling between gearbox and impeller failed.
10/5/1997	Pump 3 returned to service	Coupling replaced.
11/3/1997	Pump 1 & 2 inspection	2 small cracks discovered, no continued propagation.
11/30/1997	Pumps all shut down	Install bulkhead gate slot sluicing system
12/9/1997	Pumps returned to service	
1/7/1998	Pumps all shut down due to high water in the river	Pumps 1 & 2 inspected for continued cracking, no additional cracking was discovered
3/10/1998	Pumps all returned to service	High water receded to allow pumping.
3/21/1998	Pump shut down due to high water in the river	
4/7/1998	Pumps return to service	High water receded to allow pumping.
4/30/1998	Pump 3 shut down	Bearing failure discovered after increased runout and temperature readings.
7/21/1998	Pump 1 & 2 inspection	3 new cracks discovered, all were very short, no repairs were made.
9/11/1998	Pump 3 returned to service	Pump 3 is restarted after replacement of the shaft and bearings, and impeller flange. Dynamic balancing was completed. Manufacturer recommended no operation above 350 rev/min.
11/24/1998	Pumps shut down	High water in the river. Dewatering to allow cleaning of intake structure sump.